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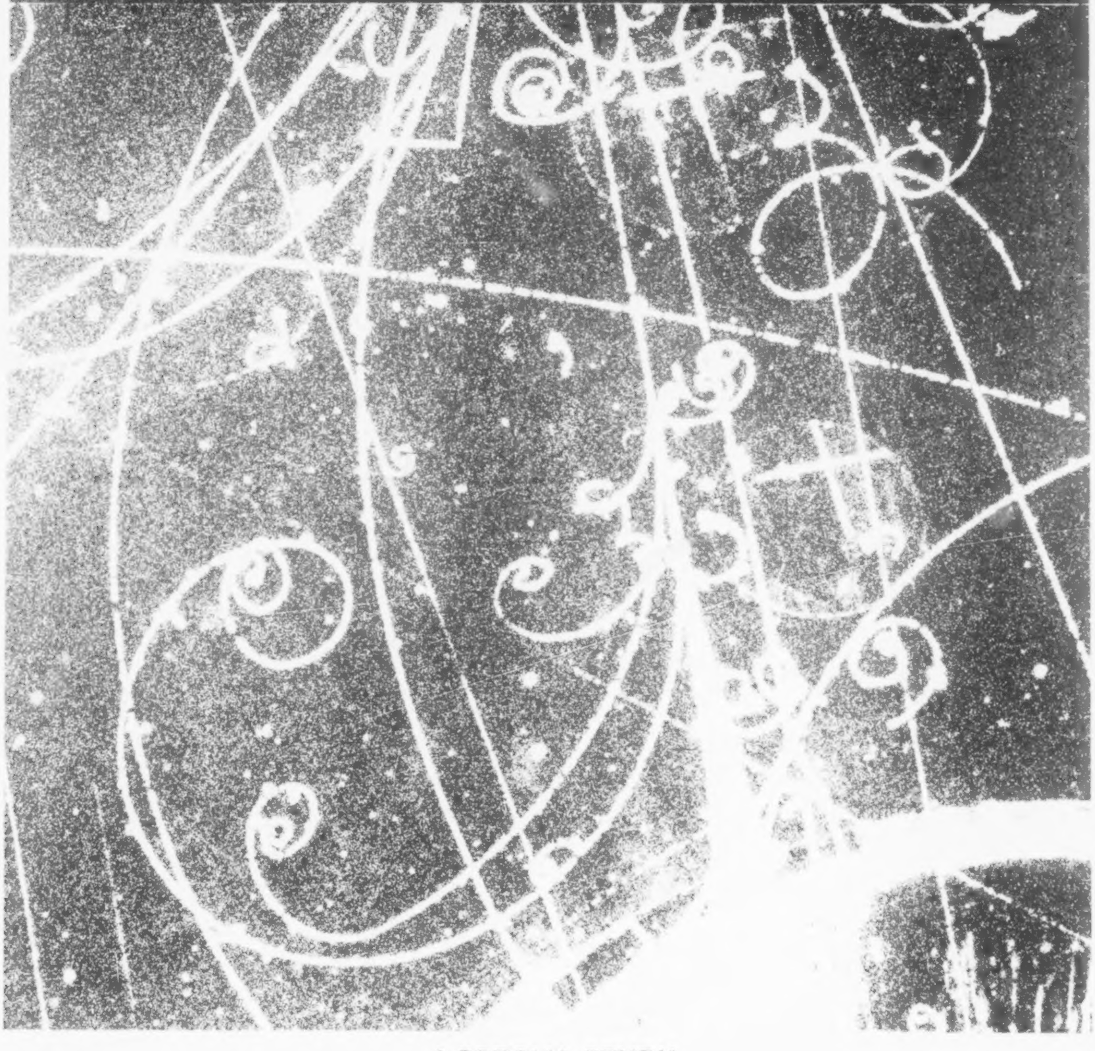
Risks and Benefits of Building the Superconducting Super Collider



A SPECIAL STUDY

J932-36

RISKS AND BENEFITS OF BUILDING THE SUPERCONDUCTING SUPER COLLIDER

The Congress of the United States
Congressional Budget Office

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NOTES

Details in the tables may not add to totals because of rounding.

All years in this report are fiscal years, unless otherwise noted.

All costs are given in constant fiscal year 1988 dollars, unless otherwise noted.

Cover photograph courtesy of the Fermi National Accelerator Laboratory of Batavia, Illinois. The photograph shows a particle interaction in the 15-foot bubble chamber at Fermilab.

PREFACE

The Superconducting Super Collider (SSC) is a proposed new particle accelerator, which would advance the state of high-energy physics. The next Congress will be faced with the choice of whether to begin construction of the accelerator, pursue an alternative, or defer the decision until further research reduces current technological uncertainties. In response to a request from the Senate Budget Committee, this special study analyzes the potential risks and benefits of building the SSC. In keeping with the Congressional Budget Office's (CBO) mandate to provide nonpartisan analysis, no recommendations are made.

Philip Webre of CBO's Natural Resources and Commerce Division, assisted by Kuljeet Kalkat, wrote this report under the supervision of Elliot Schwartz. Everett M. Ehrlich provided valuable assistance in the initial phases of the project. Robert Hunter, Director of the Department of Energy's Office of Energy Research, and Robert Diebold and the Staff of the Department of Energy's SSC Division provided many helpful suggestions and comments. The author wishes to thank Norman Blackburne, Judith Bostock, Desiree Di Mauro, Daniel Kaplan, Leon M. Lederman, Paul Maxwell, David H. Moore, Wolfgang K. H. Panofsky, Christopher Quigg, Robert L. Riemer, Burton Richter, Benno Schorr, Robert Siemann, Michael Sieverts, W. Edward Steinmueller, R. William Thomas, and Stanley Wojcicki for their helpful comments. Amanda Balestrieri edited the manuscript. Margaret T. Cromartie, Patricia Joy, and Gwen Coleman typed the many drafts, and Kathryn Quattrone and Nancy H. Brooks prepared the report for publication.

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October 1988

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SUMMARY

To preserve the momentum of high-energy physics research in the United States, the Department of Energy (DOE) is planning the construction of a particle accelerator--the Superconducting Super Collider (SSC)--that has higher energy levels than the current generation of accelerators. The Congress has thus far appropriated $205 million for the SSC, including $100 million for fiscal year 1989, mainly for research and development (R&D) and associated equipment. The construction of the SSC, not yet approved, will cost much more: DOE estimates the total costs for the SSC and associated facilities will be $5.3 billion in current dollars (in fiscal year 1988 dollars, the estimate is $4.4 billion).

DOE is scheduled to recommend a site for the SSC in November or December of this year; the Administration may ratify this choice or leave the decision to the incoming President.[1] In any event, the next Congress is likely to be confronted with the choice of whether to appropriate funds for construction. Actual construction of the SSC is scheduled to take eight years, barring any delays. This report analyzes the risks and benefits of budgetary choices facing the Congress.

THE SUPERCONDUCTING SUPER COLLIDER

The purpose of the SSC is to investigate the basic nature of matter without the expectation of any near-term use of the results. Over the decades, physicists have developed a "standard model," which explains a great deal of the behavior of matter and energy in the universe. Despite its achievements in explaining such behavior, the standard model cannot be complete since it involves many arbitrary assumptions. By exploring higher energy levels, physicists hope to expand the model by discovering certain particles and phenomena that have so far existed only in theory.

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[1] The finalist sites are located in seven different states: Arizona, Colorado, Illinois, Michigan, North Carolina, Tennessee, and Texas.

The size and strength of the SSC are largely determined by the high energy levels needed to see the phenomena of current scientific interest. It is designed to contain two proton beams, each with an energy of 20 trillion electron volts. The most powerful facility currently in operation in the United States at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, has an energy of 0.9 trillion electron volts per beam. At 53 miles in circumference, the SSC's racetrack-shaped rings will be more than 10 times the size of the Fermilab facility and three times the size of the next largest accelerator currently planned.

At the heart of the SSC are two beams of protons circling in opposite directions in two intersecting rings, each composed of roughly 5,000 superconducting magnets. When the proton beams intersect in chambers called interaction regions, some protons from each beam will collide with some protons from the other, causing their constituent particles to interact. Specialized detectors will measure the energy and trajectory of these interactions and then store this information for later analysis.

BUDGETARY ISSUES

DOE currently projects that the SSC will cost $4.4 billion in constant fiscal year 1988 dollars (throughout this report, all dollars are fiscal year 1988 dollars, unless otherwise noted). Construction of the accelerator itself accounts for roughly $3.2 billion (18 percent of which is designated for contingency costs), almost three-quarters of total project costs. The specialized detectors are projected to add $719 million, and research and pre-operating costs account for another $440 million. In addition, DOE estimates that the SSC will cost $270 million per year to operate. (These estimates were made before Congressional appropriations for fiscal year 1989.)

DOE states that its estimate is accurate within 10 percent, given that the site has not been selected and the final design studies have not been performed. Thus, the DOE estimate covers a range of $3.9 billion to $4.8 billion (see Summary Table 1). The relative certainty for each category of the estimate has not been published by DOE.

The Congressional Budget Office's (CBO's) technical analysis in Summary Table 1 examines the major components of DOE's current estimate for internal consistency. The lower bound of the technical analysis is well within the stated range of confidence for the DOE estimate, while the upper bound is $300 million above the range of confidence and more than $725 million above DOE's average estimate.

The historical analysis in Summary Table 1 simply takes the current DOE estimate and increases it by the average cost increase for accelerators built by DOE during the 1980s. DOE has built four accelerators in the 1980s and the average cost increase in constant dollar terms was 46 percent. Two of the accelerators were on budget and two suffered from exceptionally high cost escalation. No analysis of the cost increase for each category of the estimate was made because future cost increases may result from different sources.

SUMMARY TABLE 1. SSC BUDGET ESTIMATES
(In millions of fiscal year 1988 dollars)

Category	DOE Analysis[a]	Technical Analysis[b]	Historical Analysis[c]
Construction	3,210	3,210-3,480	n.a.
Research and Development[d]	274	274	n.a.
Detectors	719	890-1,175	n.a.
Pre-Operating	172	172	n.a.
Total	3,937-4,812	4,546-5,101	6,398

SOURCE: Congressional Budget Office, based on data from the Department of Energy.

NOTE: n.a. = not applicable.

a. Current estimates by DOE, made before Congressional appropriations for fiscal year 1989.

b. Adjusted by CBO for internal consistency.

c. Adjusted by CBO according to previous DOE cost performance. No component-by-component analysis was made because future cost increases may not result from the same sources.

d. Does not include $80 million in research and development performed between 1984 and 1987.

Historical Cost Escalation as a Guide for the SSC

How relevant is the experience of building past accelerators? The final costs of the two immediate predecessors to the SSC--the Energy Saver and Tevatron I at Fermilab--were 64 percent and 122 percent, respectively, above their initial estimate. In another case (the Isabelle accelerator at Brookhaven National Laboratory), there were so many technical problems that the effort was abandoned before completion. On the other hand, DOE built Tevatron II and the Stanford Linear Collider with no, or only minor, cost escalation. Furthermore, much of the cost escalation occurred during the R&D phase, after the projects were authorized, but before actual construction began. Since the SSC's R&D program is well advanced, proponents argue, substantial cost escalation is unlikely. Much of the SSC technology was originally developed for the Energy Saver and Tevatron I, and this experience may help DOE avoid some of the cost escalation caused by difficulties with new technologies. The SSC is, however, much larger than those projects and has many more components, whose cost has escalated substantially with previous accelerators. Consequently, there is a high risk that the SSC will experience cost increases.

Sharing the Cost of the SSC

Although DOE expects to receive $1.8 billion in funds from nonfederal sources to help defray the costs of the SSC, even proponents have called these assumptions overly optimistic. The most commonly discussed sources of cost sharing are the state in which the SSC is to be located and the international community. Several of the finalist states, most notably Texas and Illinois, have approved public funding to help defray construction costs should the SSC be located in their state. (The Congress instructed DOE not to consider such factors when recommending a site.) International sources have expressed interest in providing in-kind assistance with magnet and detector technology. But no prospective source has committed itself to major funding and the scale of anticipated funding is beyond the level of other countries' current high-energy physics budgets.

The Federal Budget for Basic Science

Since 1970, funding for high-energy physics has declined by 10 percent in real terms, although spending on high-energy physics has risen by 72 percent in real terms since its nadir in 1975. In 1988, high-energy physics received 6.6 percent of all federal basic science dollars, down from its 1970 high of 12 percent. By contrast, the 2,200 active high-energy physicists account for only about 3 percent of all active basic research scientists. Similarly, the 600 graduate students studying high-energy physics account for only 0.6 percent of Ph.D. students in science.

The SSC would consume a substantial portion of the current federal budget for basic science. Construction costs for the SSC will average roughly $600 million per year for a five-year period. By way of comparison, in 1988, all federal agencies spent $9.0 billion on all basic research and $4.5 billion on basic research in the physical sciences. The SSC would therefore account for 7 percent of the entire basic research budget and 13 percent of basic research for physical sciences for half a decade, assuming no increase in total basic research funding. In addition, the share of the science budget going to high-energy physics would be more than doubled.

THE SSC AND ITS ALTERNATIVES

The SSC is not the only accelerator that physicists can use for their future research. The European Organization for Nuclear Research (CERN) has begun an effort to build a smaller accelerator called the Large Hadron Collider. Alternatively, physicists have also discussed construction of an electron-positron linear collider of intermediate strength in the United States.

Summary Table 2 permits a general comparison of the three major next-generation accelerators discussed in this report. The main points of comparison are cost, completion date, mass reach, and design risk. Costs are likely federal costs. The completion date indicates when the instrument is intended to become available for high-energy physics. Mass reach represents the energy level of the interactions or phenomena of scientific interest: only a fraction of the total energy from proton collisions can be used by science. Thus, while the SSC proton beams have a total energy of 40 trillion electron volts, the mass reach is only 3 trillion to 4 trillion electron volts. In Summary Table 2, mass reach is synonymous for the scientific potential of the instrument. The design risk is a qualitative assessment combining the current state of accelerator technology with the eventual ability of the instrument to perform as planned. The primary risk is not that the machine will not work, but rather that it will be less powerful or useful than its designers intend.

The SSC would be the most scientifically capable machine, but it is by far the most expensive of the near-term options. The Congress will have to decide whether the added scientific value and the lower design risk are worth the extra costs of $3 billion to $4 billion to U.S. taxpayers. Of the cost estimates, that of the SSC is most reliable: the

SUMMARY TABLE 2. COMPARISON OF MAJOR FUTURE ACCELERATORS

	Superconducting Super Collider	Large Hadron Collider	Electron-Positron Collider
Estimated Cost to the United States (Billions of fiscal year 1988 dollars)	4.5-5.1	0.6-1.0	1-2
Completion Date	Late 1990s	Late 1990s	Late 1990s
Mass Reach (Trillions of electron volts)[a]	3-4	1.0-1.5	1
Design Risk[b]	lowest	high	high

SOURCE: Congressional Budget Office.

a. Mass reach is related to energy and refers here to the scientific potential of each instrument.

b. Design risk is a qualitative assessment of the possibility that the accelerator will be less powerful or useful than originally planned.

others include estimates based on technology that is not yet developed. The SSC estimate is based on CBO's technical analysis of DOE's estimate. Others are constructed on the basis of reasonable assumptions.

The phenomena physicists seek to explain occur at mass levels of up to roughly 1 trillion electron volts (Tevatron I can reach roughly 0.3 trillion electron volts), and the next round of accelerators will therefore be evaluated on their ability to provide such a mass reach. Both the SSC and the Large Hadron Collider would provide more than enough energy to study the phenomena in which high-energy physicists are interested. All machines are intended to reach that level, but the electron-positron linear collider may be unable to explore phenomena completely at the upper reaches of that range. Nevertheless, the electron-positron linear collider stands a good chance of making substantial contributions to high-energy physics.

As a scientific instrument, the SSC seems to have the lowest level of risk of any of the alternatives, although it is far from riskless. The Large Hadron Collider will require superconducting magnets of unusual design with strengths that have not yet been achieved. Similarly, electron-positron linear colliders need substantial additional research before they can achieve this energy level. The SSC relies on technology that is more certain, but it has already benefited from $105 million in R&D for magnets and other components and will need almost $250 million more. The technology for the electron-positron linear collider might also make substantial progress with $105 million, or even $250 million, for R&D. (Current R&D funding for improving the designs of electron-positron linear colliders is less than $5 million per year.)

CONGRESSIONAL OPTIONS

The initial choice before the Congress is whether or not to fund the construction phase of the SSC. If the Congress decides not to fund SSC construction in fiscal year 1990, it can choose to fund an alternative, either as a substitute or as a complement to further research on SSC technology. Options for a substitute facility include joining the effort by CERN to build the Large Hadron Collider. Alternatively, the Congress could fund research leading to the construction of an electron-positron linear collider of intermediate strength in the United States.

Defer the Decision

The Congress has already postponed building the SSC this year. Recently, Frank Press, President of the National Academy of Sciences, suggested that actual construction might be deferred while magnet research is continued and until the current budget conflict is resolved.

The Congress could continue to defer its decision about the construction of the SSC. The advantages of deferral include short-term budgetary benefits (costly SSC construction would be delayed until later) and benefits from greater certainty about magnet technology (only two of the eight prototype superconducting dipole magnets DOE has built so far have been even partially successful). Furthermore, benefits are already flowing from the SSC superconducting magnet research program to industry. In addition, deferral could allow the Congress to continue funding research on the alternative collider options. Then, when the research on the various instruments is sufficiently mature, the Congress will be able to choose among them. There may be few costs to bear from a short delay: despite having been postponed for two years already, the SSC has not experienced a substantial real cost increase above the initial proposal. Furthermore, U.S. high-energy physicists will not be without work, since they are just now beginning to explore new phenomena with two new instruments that were recently commissioned.

On the other hand, deferring the SSC may in turn defer other high-energy physics projects, since DOE's budget may not be able to accommodate them all simultaneously. If the SSC is unlikely to reach the construction phase, it would be better to cancel it sooner rather than later. Deferral of the decision to cancel would only commit valuable resources to a wasted task.

Build the SSC

Unless there are delays in the schedule, the SSC will set the most rapid pace of any of the alternatives in terms of providing access to high energy levels and hence potential scientific discoveries. The Congress must decide how much it is willing to pay to speed up discoveries in high-energy physics. The high-energy physics community in the United States wants to set a rapid pace, but it could continue to flourish even if the Congress chooses to fund high-energy physics at a slower pace.

The primary scientific risk of the SSC is that the large increases in the science budget needed to pay for the SSC may cause neglect in other basic science areas. (This concern will be great with regard to other physics research, especially research in other areas of high-energy physics.)

The construction of the superconducting magnets may improve the manufacturing technology for low-temperature superconductors. If there are new uses for low-temperature superconductors that would be encouraged by lower production costs, superconducting magnets may well move beyond their traditional markets in research and medical instruments. At the moment, there do not seem to be many such uses.

Low-temperature superconductor technology developed for the SSC is unlikely to contribute to the development of high-temperature superconductors. Building the SSC superconducting magnets will improve skills that may simply be irrelevant to the new high-temperature superconductors. Furthermore, deferring construction of the SSC until it can be built with high-temperature superconductors is likely to postpone its construction for 20 years or more and is not likely to save much money, if any.

Join CERN in Building the Large Hadron Collider

The United States has been informally invited to join in the process of planning and building the Large Hadron Collider (LHC), CERN's next generation accelerator. CERN is considering a proposal to build the LHC by adding a ring of superconducting magnets to the Large Electron Positron collider tunnel in Geneva, Switzerland. The CERN strategy is to build an accelerator of one-third the strength of the SSC, but still of sufficient strength to investigate the energy levels of interest and discover the phenomena that exist in this energy range, which may include many of the particles of interest. After this level has been explored, larger instruments, such as the SSC, could be built. Whether or not the U.S. government participates in the construction of the LHC, the U.S. high-energy physics community will be involved anyway, since they already participate in CERN projects.

Because the LHC proposal is at a much earlier stage than that for the SSC, the United States could influence its design substantially. CERN and its members have yet to commit themselves to its construction. U.S. participation would have to be negotiated in terms of the U.S. contribution, the role of U.S. scientists and DOE, and the rules for contract bidding by superconducting-magnet manufacturers and other component makers in the United States.

Preliminary cost estimates suggest that the LHC will cost at most $2.4 billion to $3.1 billion. The U.S. contribution would depend on the outcome of negotiations with CERN on U.S. participation. Assuming the U.S. share is in the range of 25 percent to 33 percent, the LHC would cost U.S. taxpayers between $600 million and $1.0 billion, a savings of $3.5 billion to $4.5 billion relative to the $4.5 billion to $5.1 billion required by the SSC.

The principal scientific benefit of the LHC would be to permit U.S. high-energy physics to explore new energy levels at a lower cost than the SSC. But the LHC has lower energy levels than the SSC, which may preclude observation of some additional interesting phenomena. There would also be one less instrument worldwide, meaning that fewer experiments could be performed, and more of the available instrumentation would be concentrated in one location in Europe. Moreover, building the LHC instead of the SSC or an electron-positron linear collider would leave the United States without a state-of-the-art particle accelerator.

The principal technological benefits of the LHC should come from the cross-fertilization of European and U.S. manufacturing techniques for magnets and other components, assuming that negotiations solve conflicts in international contract bidding. But some of the technology benefits that might result if the United States pursued the SSC alone would be reduced. However, if CERN pursues the LHC without U.S. participation, many technology spinoffs would be worldwide anyway. Other technological outcomes will depend on the negotiations about

U.S. participation: unless U.S. superconducting magnet makers and other component suppliers receive contracts, there would be few spinoffs for U.S. industry. Moreover, because the LHC would be located in Geneva, Switzerland, there would be no local spinoffs for the United States.

Since it is limited by the size of existing facilities, the LHC must make more technical compromises than the SSC. Its very strong superconducting magnets are just beyond the capability of current technology and are of an unusual design. Furthermore, the LHC might have to be run at a very high collision rate, one that current detector technology cannot capture. Thus, the LHC has a greater degree of design risk associated with it than does the SSC. The LHC would share the Large Electron Positron collider tunnel, and, therefore, these machines might conflict with each other for experiment time and repairs. In addition, because there would be only one large machine worldwide, malfunctions could stop all work at the highest energy levels until fixed. Lastly, the European members of CERN might decide not to fund the LHC, leaving the Congress in its current dilemma.

Build an Electron-Positron Linear Collider

The SSC and the LHC both work using high-energy proton beams. For technical reasons, accelerators that use electrons and positrons need less energy to study the same phenomena. This feature could eventually allow electron-positron linear colliders to achieve energy levels above those feasible for proton-proton accelerators, prompting some to suggest that an electron-positron linear collider be built instead of the SSC. Such a machine would be a larger version of the recently commissioned Stanford Linear Collider. While the DOE panel on alternative accelerator technology found that it would be at least 15 to 20 years before such an accelerator could match the capabilities of the SSC, it suggested that an intermediate-energy machine, perhaps approaching the mass reach levels of the LHC, could be researched, designed, and built within the next 10 years. Such a machine is not feasible or cost effective given current technology, but DOE has a major R&D program to enhance electron-positron linear collider technology. Whether or not the SSC is built, it is clear that, barring breakthroughs in technology, the proton-proton technology it uses cannot be scaled up to energies higher than the SSC because of the cost. Electron-positron linear colliders are, therefore, the leading candidate for future accelerator design.

Much of the technology for the electron-positron linear collider is as yet undeveloped. With the understanding that preliminary estimates are therefore surrounded by a high degree of uncertainty, the calculations suggest that an electron-positron linear collider would cost roughly $1 billion to $2 billion.

The principal scientific benefit of building an electron-positron linear collider with a mass reach approaching 1 trillion electron volts is that it would reach new energy levels for a lower total cost than the SSC, thus freeing up funds for other science, including other high-energy physics. Compared with joining the LHC, it would increase the number of instruments available to perform high-energy physics experiments and ensure that the high-energy physics community in the United States had a machine at the forefront of high-energy research. Such machines, however, will rely on developments in technology that may not occur. Electron-positron linear colliders carry the risk of never being able to reach these high energy levels economically, although they stand a good chance of reaching levels that are high by current standards. Furthermore, the recently commissioned Stanford Linear Collider, which is intended to test the new electron-positron linear collider technology, has been temporarily shut down because of technical problems, although many of those problems stem from recycled equipment from an older accelerator.

CHAPTER I

INTRODUCTION

Since 1945, the federal government has supported high-energy physics generously and funded the construction of ever larger particle accelerators. These scientific instruments have deepened the understanding of particle physics and produced a theory--the so-called "standard model"--that now dominates physicists' view of the world.[1] Extending the standard model's theories now requires substantially more powerful instruments than currently exist.

The latest accelerator proposed for construction in this series is the Superconducting Super Collider (SSC). The SSC is larger, more sophisticated, and more expensive than any accelerator yet built. It is designed to have two racetrack-shaped rings, each composed of a vacuum chamber surrounded by approximately 5,000 superconducting magnets and containing a proton beam with an energy of 20 trillion electron volts.[2] The most powerful facility currently in operation in the United States at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, has an energy of 0.9 trillion electron volts per beam.

The Congress has funded research and development (R&D) on various aspects of the SSC, most notably the superconducting magnets, since 1984. R&D costs for the SSC have thus far totaled $205 million, including funds appropriated for 1989 (all years are fiscal, unless otherwise noted). The Department of Energy (DOE), which funds most of U.S. high-energy physics and is in charge of the SSC, estimates that building the SSC will cost over $5.3 billion in current dollars (the constant dollar estimate is $4.4 billion in fiscal year 1988 dollars). This report analyzes the benefits, costs, and risks of constructing the SSC and presents some of the options that the Congress might consider.

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[1] This report uses particle physics and high-energy physics interchangeably when referring to contemporary events. Particle physics is an older field of study; its high-energy phase began relatively recently.

[2] One electron volt is the energy gained by an electron when accelerated by one volt. See the glossary at the end of this report for definitions.

WHAT IS THE SUPERCONDUCTING SUPER COLLIDER?

The standard model for particle physics has been refined to describe two sets of fundamental particles--quarks and leptons--that are the "basic" building blocks of all matter.[3] (According to the model, neutrons and protons are made up of quarks, while the electron itself is one type of lepton.) Physicists also believe that the four fundamental forces of nature (electromagnetism, gravity, the strong force holding atomic nuclei and their components together, and the weak force governing radioactive decay) were unified at the creation of the universe when energy levels were higher. In this manner, the standard model is consistent with the "big bang" theory of cosmology.

Despite its many successes in explaining the behavior of subatomic particles, the standard model cannot be complete since it involves many arbitrary assumptions, including parameters whose numerical value cannot be explained within the model. By exploring higher energy levels, physicists hope to begin to expand the model to discover explanations for these parameters. As a first step, the SSC, if successful, would expand the current theory that explains the unity of the electromagnetic and weak forces. (Similarly, Maxwell's equations, together with Faraday's experiments, in the 19th century showed that electricity and magnetism were actually different expressions of the same force--electromagnetism.) The theory unifying these two forces is one of the notable successes of the standard model. In order to accomplish this unification, physicists have assumed the existence of a particle, often called a Higgs Boson, that provides for certain theoretical needs.[4] The Higgs Boson has never been observed, although other particles predicted by that unification theory were discovered by researchers at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland, in 1983. Scientists postulate that it can be found only by using energy levels beyond those achievable by the current generation of accelerators. A major task of the SSC is to confirm the existence of the Higgs Boson.[5] In addition, researchers hope to discover other new particles--for example, new types of quarks--and generally investigate phenomena assumed to exist at this higher energy level.

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[3] For a description of these particles and how they fit into the standard model, see Leon Lederman, "To Understand the Universe," *Issues in Science and Technology*, vol. 1, no. 4 (Summer 1985), pp. 58-61.

[4] Marintus J. G. Veltman, "The Higgs Boson," *Scientific American* (November 1986), pp. 76-84.

The process of uniting the forces is also of great interest to cosmologists (scientists who study the origin, structure, and space-time relationships of the universe), since the unification of forces provides insight into the very beginnings and eventual end of the universe. Current accelerators can explain phenomena that occurred within 10^{-10} seconds after the big bang. The SSC would carry that knowledge further back to 10^{-13} seconds.[6]

The SSC in Operation

A small linear accelerator in the SSC will produce protons that will be sent through three accelerator rings--the low-energy booster, the middle-energy booster, and the high-energy booster--that will increase the energy of the protons in three steps. After they have been brought up to sufficient energy, the protons will be injected into the two main rings of superconducting magnets. There, the beams of protons will receive their final acceleration and the superconducting magnets will steer them into collision paths. After a day or more, the number of uncollided protons will drop to too low a level, and the main rings will need to be reloaded.

At the heart of the SSC, therefore, are the two beams of protons. The proton beams will be circling in opposite directions in two separate rings, which will be mounted directly on top of each other in an underground tunnel. The rings are designed to intersect at first in four, and eventually in six, chambers called interaction regions. When the proton beams intersect, some protons from each beam will collide with some protons from the other beam. (By having two moving objects collide, physicists are able to increase the energy capability of particle accelerators. A conventional analogy would be the difference between two cars colliding head on on the freeway versus one car running into a parked car.) The collisions of the protons will cause their constituent particles to interact. Specialized detectors will measure the energy and trajectory of these interactions and then store this information in computers for later analysis. The patterns of particle movement and energy that physicists find on subsequent examination will indicate whether or not they have found evidence of the particles they seek.

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[5] SSC Central Design Group, *Conceptual Design of the Superconducting Super Collider* (Berkeley, Calif.: SSC CDG, 1986), pp. 34-36.

[6] "Superconducting Super Collider," *Supercurrents* (March 1988), pp. 12-16. See also David Schramm and Gary Steigman, "Particle Accelerators Test Cosmological Theory," *Scientific American* (June 1988), pp. 66-72.

The physical parameters of the SSC are determined by the need to contain and direct the two high-energy proton beams. The rings of the SSC, at 53 miles in circumference, will be three times the size of the next largest accelerator (currently under construction in Europe) and more than 10 times the size of the biggest existing U.S. accelerator (the Tevatron at Fermilab). Energy containment means that the magnets that operate the SSC have to be very powerful. Conventional magnets are not strong enough--with conventional magnets, the SSC would have to be much larger. Therefore, the SSC Central Design Group, which is composed of high-energy physicists under contract to DOE, turned to superconducting magnets. (These magnets have the added advantage of reducing electricity costs, since they have no resistance to electrical current.)

The collider rings themselves are composed largely of the superconducting magnets resting inside cryostats--thermoses of liquid helium--that keep them very cold. The main rings are designed around nearly 7,700 dipole magnets, which keep the proton beams on course, and nearly 1,800 quadrupole magnets, which focus the proton beams. The dipoles, each 17 meters long, are longer than most accelerator superconducting magnets previously built. The quadrupoles, on the other hand, are comparable to the magnets in Fermilab's Tevatron, roughly 4 meters long. Most of the preconstruction research has concentrated on the dipole magnets.

CURRENT STATUS OF THE SSC

To date, the Congress has funded $205 million of SSC costs, including the next stage of SSC research, while withholding authorization for actual construction. At the same time, DOE is still trying to choose the best location for the SSC.

The Cost of the SSC

DOE currently projects that the SSC will cost $5.3 billion in current dollars. (This estimate was made before Congressional budget appropriations were completed for fiscal year 1989. Since the Congress did not grant the administration's request, total project costs will be different from this estimate.) Actual construction is to be spread over eight years. In 1988 dollars, the DOE cost estimate is $4.4 billion dollars. Construction of the accelerator itself--roughly $3.2 billion (including the superconducting magnet system projected to cost more than $1.0 billion)--accounts for almost three-quarters of these total project costs. The detectors will add another $719 million, and research and pre-operating costs account for another $440 million. Despite the inclusion of over $550 million in contingency costs in the construction estimate, the ultimate price may be higher. (The SSC costs and their associated budgetary risks are discussed in Chapter III.) In addition to construction costs, DOE estimates that the SSC will cost $270 million per year to operate.

Current Funding

The Congress has appropriated $100 million for 1989 for the SSC: $84 million for R&D, operating costs, and preliminary engineering and design, and $16 million for capital equipment related to research. This appropriation is an increase from the 1988 level of $25 million, but less than the $363 million requested by the President. The increased appropriations will allow DOE to undertake the next phase of research on the magnets, but the Congress has not approved any funds for construction.[7]

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7. *Energy and Water Development Appropriation Bill, 1989*, Report No. 100-381, Senate Committee on Appropriations, to accompany H.R. 4567, 100:2 (1988), pp. 133 and 134.

Location

The location of the SSC has yet to be decided. There are currently seven finalist sites, each in a different state: Arizona, Colorado, Illinois, Michigan, North Carolina, Tennessee, and Texas. The National Academy of Sciences recommended these sites to the Secretary of Energy out of 43 sites initially submitted for consideration.[8] Currently, DOE is conducting an environmental evaluation. The Secretary of Energy is expected to make his recommendation to the President in November or December of 1988, but the final decision could be left to the next administration.

EVALUATING THE SSC

The next Congress will be confronted with the decision of whether or not to build the SSC. The SSC, like all science projects, is a risky investment: it may produce many discoveries and technology spinoffs or it may produce few such benefits in proportion to its cost. Furthermore, no quantitative measure of its output in terms of knowledge is possible. Consequently, there is no simple measure of the SSC's social rate of return--the usual economic standard for measuring the benefits of a public investment. As a result, policymakers must make a qualitative judgment about the potential risks and benefits associated with building the SSC.

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8. National Academy of Sciences, *Siting the Superconducting Super Collider* (Washington, D.C.: National Academy Press, 1988). New York had been on the list of finalist states, but removed itself from consideration.

CHAPTER II

THE SSC AND THE PUBLIC INTEREST

The Superconducting Super Collider serves several public interests. Some are simply unmeasurable, while others cannot be measured directly. Because of the measurement problems, this analysis of the risks and benefits concentrates on how the SSC fits into the current federal portfolio of basic science research, whether the SSC favors instrument-intensive science, and which technologies are most likely to be helped by the SSC and to what extent.

BASIC SCIENCE AND THE PUBLIC INTEREST

In his analysis of the relationship of basic research (as opposed to mission-oriented research) and society, Leon Lederman, the director of the Fermi National Accelerator Laboratory, puts forward four overlapping reasons why these projects are in the public interest:[1]

- They provide the intangible benefit of general knowledge;
- They help recruit and train the next generation of scientists;
- They provide knowledge that eventually may have some practical application; and
- The process of solving scientific problems can produce collateral knowledge and instruments that may be useful in areas other than the original fields.

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[1] Leon Lederman, "Viewpoint from Fundamental Science" (report prepared for Fermi National Accelerator Laboratory, February 1982). For a similar analysis, see Leon Lederman, "The Value of Fundamental Science," *Scientific American*, vol. 251, no. 5 (November 1984), pp. 40-47.

Intangible Benefits

Science can be enjoyed for its own sake. There are science publications for the nonprofessional, science pages in the daily press, and even popular science television shows. Basic science research helps satisfy a human thirst to understand the universe. Such research also increases the knowledge of the general public and sets standards for the discipline of scientific inquiry, which may carry over into other aspects of cultural life. In addition, the United States derives substantial international prestige from its scientific accomplishments. These unmeasurable benefits, however, provide no substantive basis for ranking spending on basic science projects, other than inherent popular appeal.[2] Since scientific progress is, by and large, a slow and cumulative process, rankings based on popular appeal seem inconsistent with long-range planning.

Training Scientists and Technologists

Basic research inspires and trains many scientists and technologists.[3] This argument maintains that it is in reading about the big bang, dinosaurs, and other awe-inspiring, but not necessarily practical, expressions of science that each generation is recruited to science. More importantly, scientific training beyond undergraduate college courses often occurs working with professors on academic (meaning basic) science. Graduate students working on these projects move into industry where their training may be useful.

This criterion for support, however, does not help decide among alternative sciences each bidding for the federal dollar. Presumably, most good basic research projects will train the junior scientists and graduate students in their discipline. On the other hand, some

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2. While it is possible to say that one given experiment is more important for the progress of physics than another, it is difficult to say whether advancement in physics is more important for the advancement of human knowledge than advancement in biology or any other basic science endeavor.

3. The president of the National Academy of Sciences, Frank Press, recently argued that "preserving the human resource base" in science should receive the highest priority in science budgeting. See Frank Press, "Sorting Through the Stress and Internal Dissension of U.S. Science and Technology," *New Technology Week* (May 2, 1988).

research programs may train more graduate students than others for the same level of spending.

Even so, the number of scientists and technicians involved in a project is not necessarily the only indication of the aggregate level of training. For instance, in the early 1970s, much of the output of accelerators was photographic plates (much like the cover of this report), which were then inspected visually to find particular patterns. This procedure was relatively labor intensive. Computer programs that recognize patterns now accomplish the same task much more rapidly with much less direct labor. While this example is extreme, replacing direct labor with equipment and technology occurs in all projects. The amount of labor varies with the technology of the science, and with the cost of labor compared with the cost of the technology. Judging the training benefits of a scientific program by counting heads fails to acknowledge this dynamic process. Funding projects entirely on this basis could also provide the incentive to use obsolete, labor-intensive methods of research.

Some argue that it is on large projects like the SSC that labor-saving scientific technology is developed. It is not so pressing to automate instrumentation in small science, this argument alleges, because there are no significant economies of scale to be realized. Yet, once developed by large projects, the labor-saving techniques can spill over to smaller projects.

With these caveats in mind, it should be noted that the field of high-energy physics does not train a substantial number of scientists. DOE estimates that currently 600 graduate students nationwide are studying high-energy physics. By contrast, in 1986, there was a total of 102,000 Ph.D. students in science, excluding psychology and social sciences. Thus, high-energy physics accounts for only a small fraction of science education in the United States. In addition, the number of technicians working on high-energy physics projects is comparable to the number of graduate students studying high-energy physics.[4]

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[4] Calculated from Department of Energy, *Report of the HEPAP Subpanel on Future Modes of Experimental Research in High Energy Physics* (July 1988), pp. 3 and 26. The number of engineers and technicians working on high-energy physics projects is assumed to equal 29 percent of the number of physicists plus physics graduate students. For the total number of Ph.D. students in physical science, see National Science Board, *Science and Engineering Indicators--1987* (November 1987), p. 196.

High-energy physics, therefore, does not provide a substantial number either of technicians or of graduate students, relative to its level of federal funding.

Practical Applications

Numerous examples of the links between basic science and practical applications exist. Solid-state electronics would be impossible without the knowledge of quantum mechanics, which was at the frontier of particle physics early in this century. The discovery of the genetic material DNA preceded its biotechnology applications by decades. The relationship between basic and applied research, however, is often oversimplified. Conventional analysis presents a pipeline where discoveries flow from basic research to applied research, and then to product or process development. The interaction of the different phases of research are actually much more complex. Sometimes it is in the application stage that gaps in basic research findings become apparent, or that solutions to these problems suggest themselves. In part because of the lack of a simple relationship between basic research and later research, there is no simple relationship between research and development and economic growth.

The output of both basic and applied research is information. In neither case is the information used directly by the final consumer. Both are used as an input to developing a product or process. From an economic perspective, one can think of the entire R&D process as a sequential search for the products or processes with the greatest economic utility.[5] Basic research narrows the search. Applied research further restricts the range of feasible applications. Development is the selection of one or more discoveries for commercial introduction. Overall, roughly two-thirds of R&D costs cover development.[6]

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[5] Paul A. David, David Mowery, and W. Edward Steinmueller, "The Economic Analysis of Payoffs From Basic Research--An Examination of the Case of Particle Physics Research" (policy paper prepared for the Center for Economic Policy Research, Stanford University, January 1988), pp. 18-24.

[6] For a more complete discussion of categories of R&D, see Congressional Budget Office, *Using Federal R&D to Promote Commercial Innovation* (April 1988), p. 34.

Analyses of basic science often fail to indicate that it is costly to use basic science results. To use the information produced by basic research, an organization must already possess a great deal of information, usually in the form of highly educated, and therefore expensive, employees. Thus, basic research has two cost components: discovery and use. In this sense, investments in basic research parallel investments in productive equipment: there is a fixed purchase cost and a variable use cost.

Because of these additional costs, the benefits derived from basic research must be put in perspective. For example, while modern solid-state electronics might be impossible without knowledge of quantum mechanics, it is also the case that with only the knowledge of quantum mechanics, modern solid-state electronics would also be impossible. Analyses that try to attribute all the benefits of these subsequent developments to basic research are overstating the contribution of basic science.

Technology Spinoffs

In many cases, the instruments created to perform science experiments have uses far beyond their original purpose. For instance, particle accelerators, which were originally developed to conduct physics experiments, are now used in areas as varied as medicine and the manufacture of integrated circuits. Already, the research performed for Fermilab's Tevatron I accelerator on superconducting magnets is having spinoffs for medicine via superconducting magnets, independently of the new research on high-temperature superconductors.

Several themes relevant to the SSC can be drawn from a substantial literature concerning federal government technology spinoffs and commercial innovation.[7] (For a discussion of technology spinoffs from government programs, see Appendix A.) First, federal agencies have had the greatest success with spinoffs when they were users, not just champions, of the technology in question. Second, federal agencies also played a substantial role in commercial development when they represented a large fraction of total demand for a given product. Third, while federal agencies may have played a crucial role in the development of technologies, individual programs or instruments are rarely responsible for the entire development: progress generally comes one step at a time. Lastly, even when a general area of development seems promising, an individual area may not be.

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[7] For a compendium of industry studies, see Richard R. Nelson, ed., *Government and Technical Progress, A Cross-Industry Analysis* (New York: Pergamon Press, 1982). See also Kenneth Flamm, *Creating the Computer: Government, Industry and High Technology* (Washington, D.C.: The Brookings Institution, 1988), and *Targeting the Computer: Government Support and International Competition* (Washington, D.C.: The Brookings Institution, 1987).

These points have several lessons for the SSC. Most important is that the SSC by itself is unlikely to result in more than one or two major technological developments. This limitation is, however, not inconsistent with continued support of basic research for the sake of technology spinoffs: while the Congress may expect the field as a whole or science as a whole to provide net benefits to the nation, the likelihood of an individual project doing so is quite small.

Second, the fields of technology in which the SSC is likely to play a role are probably limited. The SSC will represent the bulk of the superconducting magnet market during its construction. Consequently, from the perspective of both technology push and demand pull, the SSC may prove important to the development of a superconducting magnet industry. This is not to say that the SSC will not contribute to technical progress outside this field: rather, the SSC is similar to any other sophisticated consumer of computers and instruments, and it is no more or less likely to produce an important advance than any other major laboratory. (Some studies of CERN accelerator programs have tried to assert the contrary, but analysis of these results shows these claims are overstated. See Appendix B for an analysis of spinoffs from CERN accelerator research.)

THE FEDERAL SCIENCE PORTFOLIO

In the context of the federal budget for science, the SSC can be evaluated in terms of how it might produce scientific results that could be of use in the future. Because the SSC would be a basic science laboratory, the discussion focuses not on near-term use of the project results (not even the most ardent advocate believes SSC results will be useful in a practical sense in the near term), but on the amount of science it produces for the cost. Unfortunately, knowledge does not come in measurable units, but related measures can provide an indication of the possible benefits. Such measures include the application of basic scientific knowledge, the relationship between scientific input (people and money) and expected outputs, and the diversification of the federal science portfolio.

The SSC would occupy a substantial portion of the entire federal budget for basic science. Construction costs for the SSC will average roughly $600 million annually for six years. By way of comparison, in 1988, federal agencies are projected to spend $9.0 billion on all basic science research, but only $4.5 billion on basic research excluding the life sciences.[8] Assuming unchanged levels of real funding, the SSC would account for between 6 percent and 7 percent of the entire basic research budget and 13 percent of the physical sciences budget for over half a decade, doubling the share of the science budget going to particle physics. Unless the Congress provides for substantial growth in other relevant research agencies, the SSC may very well crowd out other basic science research. Considering the high rejection rates in science agencies--the National Institutes of Health, for instance, funds only one-third of new grant applications that have passed peer review--the knowledge that is expected to result from the SSC must be central to the advancement of particle physics in order to justify its level of funding.

One aspect of basic research that is often misunderstood is its riskiness. In "normal" times, scientists know roughly what they are looking for: they are attempting to validate or disprove results derived by theory or obtained by their colleagues.[9] For instance, before new subatomic particles are discovered, their mass and characteristics are usually known well enough to tell phenomenologists--the physicists who interpret accelerator output--what to look for. Instrument technology is also improved in a gradual manner--for instance, the SSC design is largely derived from experience with the Tevatron I accelerator at Fermilab. Thus, a large part of the risk is neither scientific nor technological. Rather, from the perspective of the public interest, the risk is economic: that the investment will produce nothing commercially useful.

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[8] *Budget of the United States Government, Fiscal Year 1989, Special Analyses*, p. J-7.

[9] "Normal" science makes a small individual contribution to a paradigm, like a piece in a puzzle, that fills out a complete picture.

One response to the risky nature of science spending is to maintain a diversified portfolio of science investments. Since no one knows which basic science will provide the most useful results or even, in actuarial terms, what the pattern of returns to basic science is, one reasonable strategy is to invest equally in all sciences. This strategy can be static, giving each science a fixed percentage of the basic science budget, or dynamic, responding to perceived breakthroughs or opportunities, while maintaining a balance over time. By and large, the Congress has attempted to expand developing areas, as shown by the effort to increase research in superconductivity in response to the new discoveries. A corollary of the dynamic portfolio mix is that as fields are exhausted, federal investment should be reduced.

Figure 1 shows the share of federal basic science funds by scientific discipline for selected years. The portfolio clearly favors life sciences, whose share has risen from 36 percent of the total in 1970 to about 47 percent in 1988. Fully half of this rise came at the expense of high-energy physics, whose share has declined by more than 40 percent over the same period (from 11.9 percent to 6.6 percent). Figure 1 also shows that the big declines in the share of the budget allocated to high-energy physics came in the early 1970s (presumably after the war on cancer concentrated research in related fields).[10] The share of the science budget devoted to high-energy physics rose from a low point of 6.6 percent in 1975 to 7.4 percent in the early 1980s. Since the construction of the Energy Saver and Tevatron I at Fermilab, however, this share has returned to the 1975 level.

In the case of high-energy physics, this relative decline was also a real one. In constant 1988 dollars, high-energy physics spending fell

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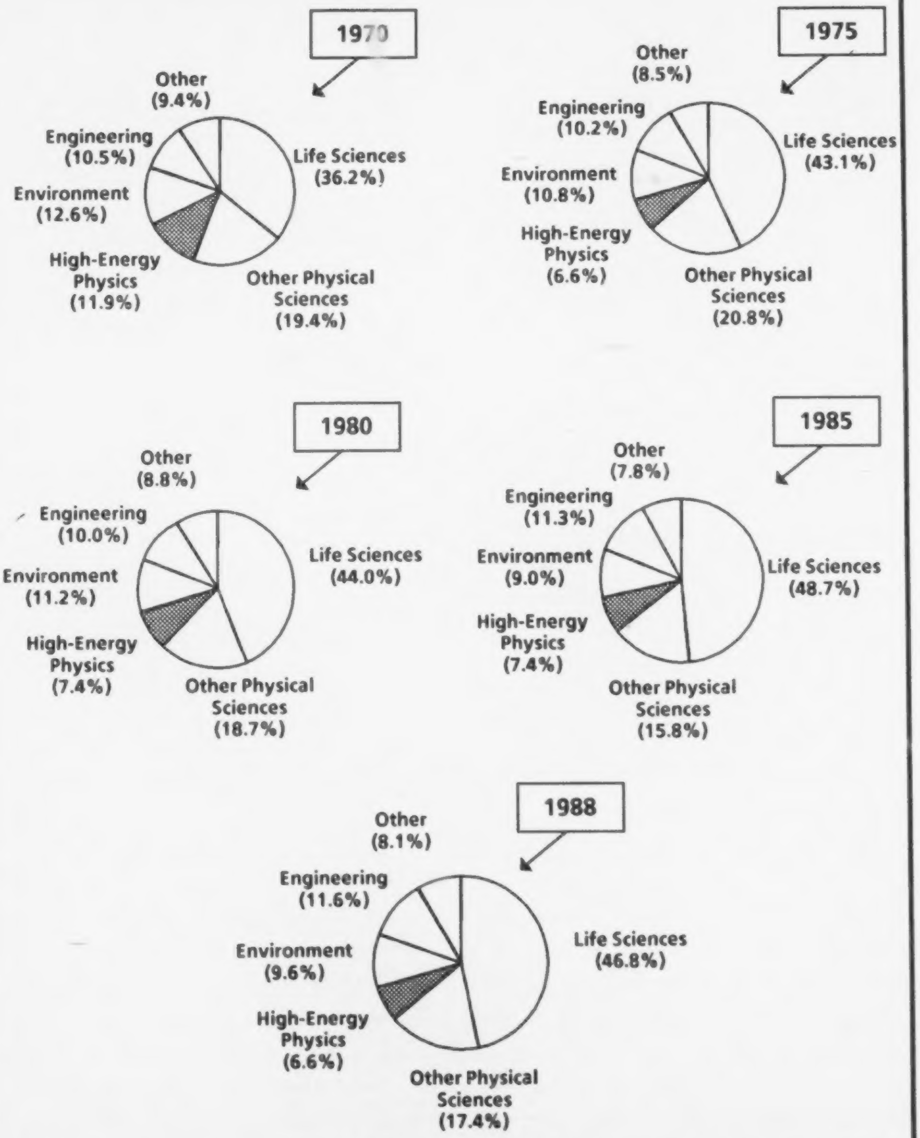
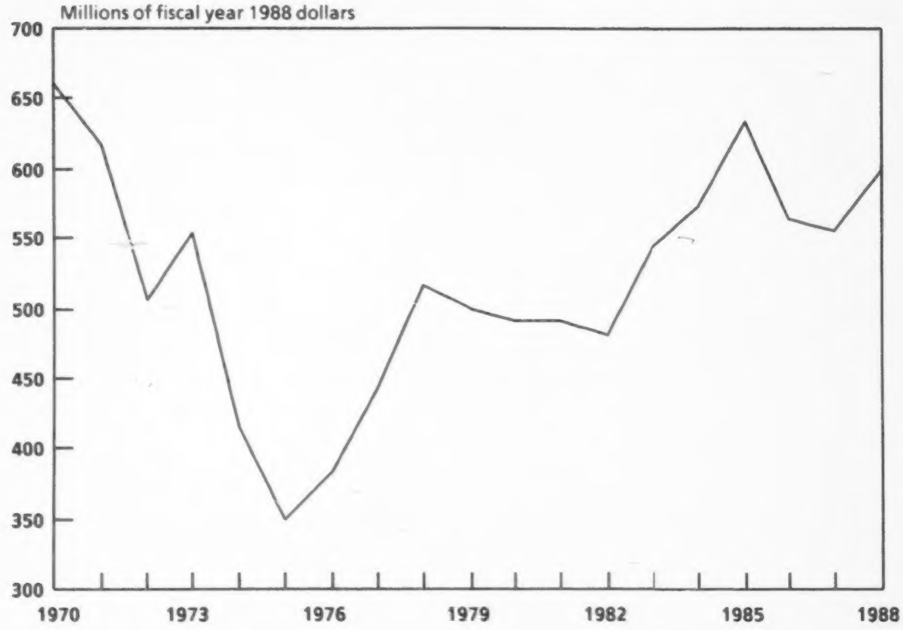
[10] Interestingly, the share of basic science spending that went to engineering and medicine, which are applied fields, increased during this period, raising questions about definitions. If the definition of basic science--as used by reporting federal agencies--changed over the period, then relative shares may be shifting for different reasons. This may especially be the case with medical research, for which the share quadrupled between 1967 and 1986, or engineering, for which the share rose by a factor of six. On the other hand, while the war on cancer increased research in many applied fields, it also increased the desire to learn more about basic biology. For detailed information about basic research spending by field of science, see National Science Board, *Science and Engineering Indicators--1987* (November 1987), p. 252.

Figure 1.
Basic Science Budget by Discipline for Selected Fiscal Years
(As a percentage of all federal basic science research)



SOURCE: Congressional Budget Office, derived from data provided by the National Science Foundation, the Department of Energy, and the National Academy of Sciences.

Figure 2.
High-Energy Physics Spending



SOURCE: Congressional Budget Office, derived from data provided by the National Science Foundation, the Department of Energy, and the National Academy of Sciences. Numbers adjusted for inflation using the gross national product deflator.

from $660 million in 1970 to $600 million in 1988, a 10 percent decline. Figure 2 shows, however, that high-energy physics spending has been growing in real terms since its nadir in the mid-1970s.[11]

This relative decline in the funding of particle physics is consistent with a diversified portfolio strategy of basic science only if particle physics is in stagnation or if life sciences are perceived as being able to provide more usable science. Observers would probably agree that particle physics has not been stagnant during the last two decades, nor is it now. Life sciences must therefore be perceived as being able to produce more usable results, although this perception is inconsistent with the notion that policy cannot judge beforehand which basic science will prove the most useful. Biotechnology itself is in part derived from the particle physics--quantum mechanics--of the early twentieth century.

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[11] Using sectoral deflators instead of the gross national product deflator would produce a generally similar pattern.

On the other hand, the Congress may be expressing a sense that particle physics may have hit a point of diminishing returns in terms of producing results usable within a few decades.[12] This is not to say that particle physics will produce ever-decreasing knowledge, but rather that particle physics may become justified by its intangible benefits, rather than by the practical application of its scientific results. (Of course, high-energy physics may still produce economically useful technological spinoffs.) The phenomena the accelerators now seek to describe may be so fundamental that, like the theories about the big bang or the extinction of the dinosaurs, they become part of the culture, not the economy. This belief would come from a perception that, rather than all basic science being the same, some research is more basic than others.[13] But this further division of basic research simply modifies, rather than solves, the dilemma: how does the Congress decide among very basic research projects?

ECONOMIES OF SCALE IN BASIC SCIENCE

Roughly 1,500 Ph.D.-level particle physicists are active in experimental work in the United States, two-thirds of whom are based at universities.[14] Universities contain a further 700 elementary particle theorists and 600 graduate students in particle physics, making a national total of 2,200 particle physicists. By contrast, in 1985--the most recent year for which numbers are available--72,200 Ph.D.-level scientists were working in all fields in the United States.[15] (Psychologists and social scientists account for 9,800 of these.) Thus, while particle physics represents only 3 percent of practicing scientists, it accounts for over 6 percent of science spending.

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[12] For a technical version of this argument, see John F. Waymouth, in "Letters," *Physics Today*, vol. 41, no. 7 (July 1988), pp. 9 and 11.

[13] Leon Lederman describes this as "very basic" research. See Lederman, "Viewpoint from Fundamental Science," p. 3.

[14] Calculated from Department of Energy, *Report of the HEPAP Subpanel on Future Modes of Experimental Research in High Energy Physics* (July 1988), pp. 1-3. Other DOE sources give similar numbers (within 10 percent to 15 percent).

[15] National Science Board, *Science and Engineering Indicators--1987* (November 1987), p. 274.

Whether more "science" takes place in large science facilities or in individual laboratories is difficult to determine, and the debate is not clearly productive. Some science questions lend themselves to small research projects and others cannot be answered by anything other than the largest pieces of equipment. Given these constraints, the scientific trade-offs become less clear. For instance, it may simply be impossible to investigate some areas of astronomy without very expensive pieces of equipment. If U.S. scientists are to work in these areas, certain large investments must be made. While the scientific trade-offs are not clear, the budgetary trade-offs are: money that goes to large instruments is not available to fund smaller-scale projects. Thus, the Congress is being asked to make choices that scientists themselves admit they are unable to make in terms of science output.

Economies of Scale in Particle Physics

Evidence suggests that particle physics is one of those fields where large instruments are the rule.[16] According to a recent Congressional Research Service survey, there are over 200 "big science" facilities or instruments--defined as costing more than $25 million in fiscal year 1984 dollars--in the United States.[17] Of these, 17 are for particle physics. In addition, most, if not all, particle physicists use these existing instruments, or their output. For instance, over 50 percent of high-energy physicists in this country use Fermilab's Tevatron complex, which is the largest accelerator currently available.[18] Furthermore,

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16. High-energy physics investments may be what economists call "lumpy"--that is, investments with an indivisible input. Just as it is impossible to discover one-quarter of a new world, it may be impossible to discover a use for one-quarter of a theory of quarks or the electroweak force. For the implications of this, see Paul A. David, David Mowery, and W. Edward Steinmueller, "The Economic Analysis of Payoffs From Basic Research--An Examination of the Case of Particle Physics Research," pp. 25-27.

17. See Congressional Research Service, *World Inventory of "Big Science" Research Instruments and Facilities* (December 1986).

18. Statement of Leon Lederman, Director of the Fermi National Accelerator Laboratory, before the Subcommittee on Energy Research and Development, Senate Committee on Energy and Natural Resources, Hearings on the Department of Energy's fiscal year 1989 budget request for the Superconducting Super Collider and the Basic Science Budget, April 12, 1988.

the leading edge in particle physics seems to follow big instrumentation, which is a concrete example of science historian Derek de Solla Price's hypothesis that science follows instruments.[19]

Recently, this hypothesis received corroborating evidence in elementary particle physics in a study examining the correlation between the number of particle physics articles and citations for each country and the energy level of particle accelerators in each country.[20] The researchers tracked the number of articles and citations in the major journals about particle physics between 1961 and 1984, and discovered that U.S. scientists dominated the field until the late 1960s, after which the European average rose. Beginning in the early 1970s, the first Fermilab accelerator went into operation and reestablished the U.S. preeminence in particle physics by every measure--number of articles, number of citations, and number of articles cited 15 times or more. Four years later, the Super Proton Synchrotron went into operation at the European Organization for Nuclear Research (CERN) facilities and European research came into ascendancy. The Germans followed the Super Proton Synchrotron with a large electron-positron collider (PETRA), and that was followed in turn by CERN's proton-antiproton collider in 1982. During this entire period, European research scored high in all the bibliometric measures. In the United States, the Tevatron I at Fermilab has just completed its first full year of operation and the Stanford Linear Collider is coming into operation. Judging from the previous pattern, U.S. particle physics should begin to rise in bibliometric scores. This reemergence may, however, be temporary as two new major accelerators--HERA in Germany and the Large Electron Positron collider at CERN--are under construction and may eclipse the U.S. instruments in output.

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[19] See Derek J. de Solla Price, "Of String and Sealing Wax," in *Little Science, Big Science...and Beyond* (New York: Columbia University Press, 1986), pp. 237- 253."

[20] John Irvine and others, "The Shifting Balance of Power in Experimental Particle Physics," *Physics Today* (November 1986), pp. 27-34. The use of articles and citations to measure scientific progress provides limited information. For a discussion of the limits of this type of analysis, see Office of Technology Assessment, *Research Funding as an Investment: Can We Measure the Returns?* (April 1986), especially pp. 29- 37. For more recent analysis, see A. L. Porter, D. E. Chubin, and Xiao-Yin Jin, "Citations and Scientific Progress: Comparing Bibliometric Measures with Scientist Judgments," *Scientometrics*, vol. 13 (1988), pp. 103-124.

Despite the bibliometric evidence cited, if an instrument is located in Europe or the United States, it does not mean that only European or U.S. scientists benefit from it to the exclusion of others. The particle physics community is international, and scientists cooperate in experiments across national boundaries. Many U.S. scientists work on CERN projects. Wolfgang Panofsky, a U.S. physicist connected with the Stanford Linear Accelerator Center, estimated that almost one-third of U.S. high-energy physicists work on CERN projects. Conversely, many CERN and other foreign scientists work on U.S. particle physics projects. Leon Lederman, the Director of Fermilab, has testified that over 10 percent of all foreign scientists working in particle physics made use of the Tevatron accelerator at Fermilab.[21] Furthermore, the recruitment of promising young scientists is worldwide: science graduate students in the United States are often citizens of other countries.

The 1976 Nobel Prize for Physics is especially illustrative in this regard; it was awarded to two U.S. scientists, Burton Richter and Samuel Ting, for their discovery of the charm quark.[22] Richter designed the Stanford Positron Electron Accelerator Ring and used that machine to conduct the experiments for which he won the prize. Ting used the existing accelerator at Brookhaven National Laboratory for his work. Subsequently, Richter worked on the conceptual design for CERN's Large Electron Positron collider, which starting next year will be the biggest machine of its type in the world, and he is currently director of the Stanford Linear Accelerator Center. Ting is director of CERN's major Large Electron Positron collider experiment and serves on CERN's Long Range Planning Committee, while continuing as a professor at the Massachusetts Institute of Technology.

Big Science and Particle Physics Budgeting

The greatest cost in big science projects that depend on a single instrument is the construction of that instrument. But particle physics has not seen much construction over the recent past, as few new instruments have been built. If anything, relative to total spending on high-energy physics, construction has been declining (see Figure 3). Spending in 1988 for particle physics construction is 22 percent of 1970 spending in real terms. By contrast, spending on operating and equipment has risen over the period, albeit primarily in the last six years, by roughly 29 percent.

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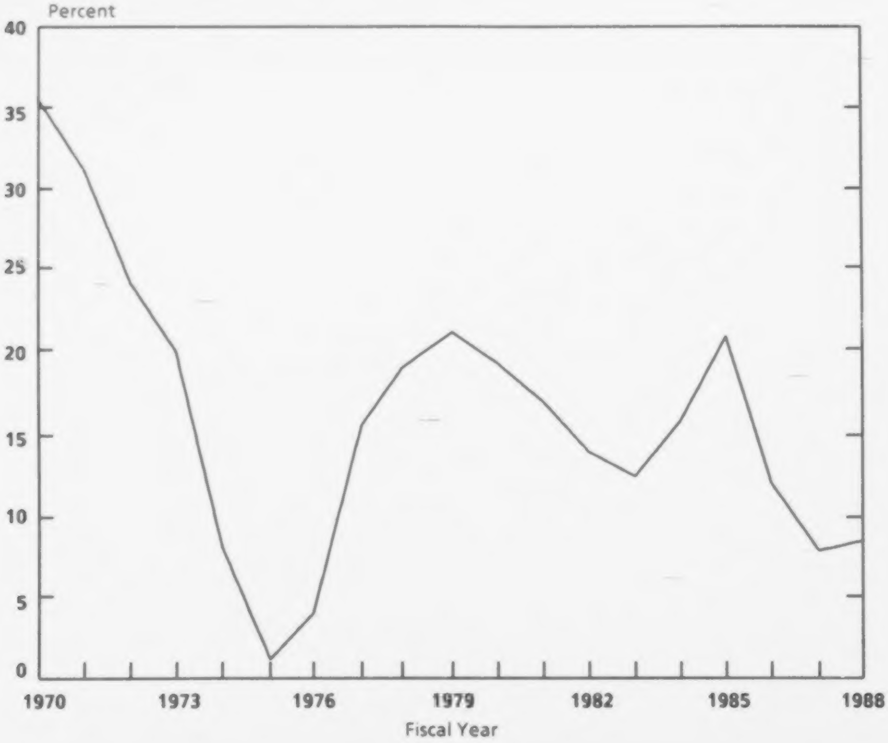
[21] Lederman, Hearings on the Department of Energy's fiscal year 1989 budget request.

[22] For more information on this discovery and a view of the international nature of the high-energy physics community, see Sheldon Glashow with Ben Bova, *Interactions: A Journey Through the Mind of a Particle Physicist and the Matter of this World* (New York: Warner Books, 1988), pp. 234-236.

Figure 3.
Construction Budget as a Percentage of Total Budget for High-Energy Physics



SOURCE: Congressional Budget Office, derived from data provided by the National Science Foundation, the Department of Energy, and the National Academy of Sciences. Numbers adjusted for inflation using the gross national product deflator.

Of course, the operation of big machines constitutes a significant fraction of all spending on operations and equipment. Operating costs differ from construction costs, however. When the machines are in operation, most of the costs are for science, as opposed to bricklaying. But when hundreds of people are working on an experiment, it may become "industrial science," taking on a different character from the traditional investigator in a laboratory. At this point, the different disciplines interact. In fact, according to proponents, the close cooperation of physicists and other researchers is one of the benefits that make accelerators powerful tools for the advancement of science.

On the other hand, the SSC will require that the Congress increase the current total investment in particle physics instruments by over 160 percent. Table 1 shows all the particle physics facilities currently in operation in the United States. (Other facilities were built, but they have been either decommissioned or are engaged in other

TABLE 1. CONSTRUCTION COSTS OF HIGH-ENERGY PHYSICS FACILITIES CURRENTLY OPERATING IN THE UNITED STATES (In millions of fiscal year 1988 dollars)

Site	Cost
Cornell Electron Storage Ring	32
Fermilab Proton Synchrotron	819
Fermilab Superconducting Synchrotron	75
Fermilab Tevatron I	96
Fermilab Tevatron II	56
Fermilab Collider Detector	61
Fermilab D-Zero Detector	48
Stanford Linear Accelerator	547
Stanford Positron Electron Project	149
Stanford Linear Collider	124
Stanford Linear Detector	51
Alternative Gradient Synchrotron	366
Total	2,424

SOURCE: Calculated from Congressional Research Service, *World Inventory of "Big Science" Instruments and Facilities* (December 1986), pp. 48-59, using gross national product deflator.

NOTE: Details may not add to total because of rounding.

work.) The cost of construction for all these facilities totaled $2.4 billion.[23] These construction figures do not include costs for R&D, however. The equivalent cost for the SSC would therefore be $3.9 billion in 1988 dollars ($3.2 billion for the SSC itself and $719 million for the detector).

SPINOFFS FROM THE SSC

Government programs that concentrate on technology have occasionally produced technology by-products whose economic effect dwarfed those of the original program. The successes of the computer and integrated circuit industries, both of which were developed largely through federal government programs, have raised the hopes for all subsequent government programs that involve advanced technology. Yet, most government research programs produce few, if any, such spinoffs.

Spinoffs from experiments in particle physics are already in widespread use. Computer software originally developed for pattern recognition in particle detectors was used to develop the computer-aided tomography (CAT) scanning machines now used in medicine. Most recently, construction of the Tevatron I accelerator at Fermilab resulted in the creation of a superconducting cable industry, which in turn permitted the creation of magnetic resonance imaging machines for medical diagnostics. (For a discussion of spinoffs from particle physics technology, see Appendix A.)

Building and operating the SSC may produce several technology spinoffs, most of which cannot be predicted in advance. The mere presence of so many highly trained personnel working on major technology problems increases the probability that valuable knowledge will be produced. A similar amount spent on other R&D in technology, however, might also produce substantial advances. The major new development being pursued by the SSC is in the technology for very large superconducting magnets. Accordingly, this section concentrates on the potential for technological and commercial advantages from the development and manufacture of the SSC's superconducting magnets.[24]

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[23] Congressional Research Service, *World Inventory of "Big Science" Research Instruments and Facilities*, pp. 48-59.

How Would the SSC Affect Low-Temperature Superconductors?

The most expensive and technologically challenging component of the SSC is the double ring of superconducting magnets, which will guide and focus the beams of protons for the collisions. The current design for the rings involves 7,680 17-meter magnets and 1,776 4-meter magnets, containing nearly 20 million meters of superconducting cable cooled to near absolute zero.[25] The use of superconducting magnets makes the SSC feasible: with conventional magnets, the SSC would have to be several times its proposed size to contain the same amount of energy. The massive use of superconductors by the SSC has raised the question of whether this demand is likely to lead to the development of a U.S. superconductor industry, the way the Minuteman II Missile and Apollo Lunar Mission systems of the early 1960s led to the development of the U.S. integrated circuit industry.

The SSC will dramatically increase the demand for superconducting magnets during the five-year process of acquiring 10,000 magnets. The current total annual production of superconducting magnets in the United States is between 400 and 600. Once the production process begins, the SSC demand will dwarf worldwide demand for similar magnets, and the industry will experience a dramatic surge in growth. It will mature in two to three years and then start an equally dramatic decline in demand toward the original level. Such spikes in growth may destabilize the industry. While the SSC contract is being filled, other buyers could be driven out of the market by a lack of supply. Once the SSC contract is completed, the tooled-up magnet manufacturers will be seeking buyers for their products. But few such buyers may exist at that time.

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[24] The SSC Central Design Group, in *Conceptual Design of the Superconducting Super Collider* (Berkeley, Calif.: SSC CDG, 1986), (referred to hereafter as *SSC Conceptual Design*), suggests that the SSC will be using "off the shelf" components for its computer network. The SSC is therefore no more likely to make a substantial advance in computer technology than is any other large sophisticated user. CBO did not undertake an analysis of detector technology, because DOE has not yet completed the design of the detectors.

[25] There are many other conventional accelerator and focusing magnets, for a total of approximately 10,000 magnets.

Wide swings in demand and supply could have negative effects on this infant industry.[26] The actual outcome depends on the extent to which the SSC brings down the manufacturing costs of, and increases the demand for, superconducting magnets. The SSC will affect the manufacture of superconducting magnets in two ways: first, in the fabrication of the magnets themselves, and second, in the fabrication of the superconducting cable used to make the magnets.

Superconducting Magnets. Table 2 shows the cost breakdown of the dipole magnets as estimated by the Central Design Group of the SSC in March 1986. The process of making or assembling superconducting magnets appears to be dominated by capital and material costs. Of total costs of $796 million, material costs account for $658 million.[27] Only 17 percent ($137 million) of the total cost of the magnet is the cost of labor. Ten percent of the costs are related to the manufacturing process: allowances for rejects, allowances for material usage, industrial fees, and storage costs. The remaining 73 percent of the costs are for components and materials.

While some of the direct costs of making superconducting magnets could be affected by the large demand of the SSC, many of the material costs could not. Apart from reduced labor costs, there could be a reduction in the allowance for rejects, material usage, factory support, storage, and procurement. A more experienced labor force would smooth out these operations and thus create the savings. On the other hand, while most components that magnet makers buy for assembly will have a labor portion in their cost, no individual component (excluding the cable) is significant as a percentage of the total cost of the magnet. Moreover, some components, like iron laminations for

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[26] For instance, these wide fluctuations in demand could permanently affect both buyers and suppliers. The period of excess demand might drive potential users to designs not requiring superconducting magnets, lowering the path of future potential sales. Similarly, the period of excess supply might discourage investment, especially research, in this depressed field, lowering the path of future potential supply. This is only one of many possible scenarios.

[27] *SSC Conceptual Design*, Attachment D, Appendix B, pp. 72-74. Converted to 1988 dollars using DOE's inflation index for energy research and nuclear construction.

TABLE 2. COST COMPONENTS OF DIPOLE MAGNETS
(As a percentage of total cost)

Category	Labor	Materials	Total
Coils			
Cold beam tube	1.0	5.0	6.0
Superconducting cable	0.0	29.7	29.7
Wedges	0.9	1.5	2.4
Main coil fabrication	1.9	0.4	2.3
Collaring	0.8	6.4	7.2
Other	0.7	0.5	1.3
Subtotal	5.3	43.5	48.9
Yoke and Helium Containment	1.2	14.2	15.4
Final Assembly Cold Mass, Cryostat	3.7	11.6	15.3
Electrical System	2.0	1.8	3.8
Magnet Interconnections	0.1	1.7	1.8
Magnetic Measurements	0.8	0.3	1.1
Factory Support	3.4	0.0	3.4
Material Procurement Allowance	0.0	1.0	1.0
Allowance for Rejects	0.5	1.3	1.8
Allowance for Material Usage	0.0	2.0	2.0
Industrial Fees	0.0	4.2	4.2
Storage and Handling	0.2	1.3	1.5
Total	17.3	82.7	100.0

SOURCE: SSC Central Design Group, *Conceptual Design of the Superconducting Super Collider* (March 1986), Attachment D, Appendix B, pp. 72-74.

the yoke, are unlikely to change their manufacturing technology in response to SSC demand.[28]

Thus, the labor component of this industry is already small and the proportionate reduction in labor costs will remain small. If, for example, the superconducting magnet industry could achieve a 20 percent savings in labor and process costs from learning and automation resulting from the SSC project, there would be a reduction of only 5.4 percent in the overall price of the magnets. Despite initial hopes, this is not a significant contribution toward maturing the superconducting magnet industry.

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[28] Another effect of automation would be an increase in the production rate, but unless long-term demand from sources other than the SSC rises sharply, the increased production rate will not be important to the industry.

Superconducting Cable. The largest single cost component of the magnet is the superconducting cable that forms the coil of the magnet. The increased demand will affect both costs and fabrication processes of the cable industry. The cable is made of niobium-titanium alloy and copper. The materials are readily available and the SSC will not test the limits of niobium-titanium production.[29]

The cables are made by a detailed process involving several steps, each requiring a high degree of precision. The process is partly automated and the surge in demand should result in further automation. The SSC is developing machines to make the superconducting cable at a faster rate. Since 50 percent of cable costs are for labor, research, and other nonmaterial costs, manufacturers are also likely to gain experience and reduce their costs.[30] The SSC Central Design Group's cost breakdown assumes both types of cost savings will occur and has scaled down the cost of the cable from current costs in its estimate.

Overall Effects. Since cable costs account for 30 percent of the cost of superconducting magnets, a reduction in the nonmaterial costs of the cable of, for example, 20 percent to 40 percent more than assumed by the SSC Central Design Group would reduce magnet costs by 3 percent to 6 percent. On top of the 5.4 percent saved in magnet fabrication, this means that, under the most optimistic assumptions, the SSC would reduce magnet costs by only 10 percent to 15 percent, not really enough to stimulate many new applications, although the SSC may play a role in the diffusion of superconductor technology to industry and serve as a general demonstration project.[31]

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29. It is possible, however, that the few producers of this rare alloy could set monopoly prices once the highly inelastic demand of the SSC is determined. Thus, the price of the principal raw material used to make the cables for superconducting magnets could increase.

30. The 208 kilograms (kg) of cable per magnet will cost $28,000. A superconducting cable is 45 percent niobium-titanium and 55 percent copper. At $154 per kg for niobium titanium and $2 per kg for copper, the material costs in the cable are ((154 * 0.45) + (2 * 0.55)) * 208 = $14,643 per magnet. The cost of niobium-titanium used here is the average of the range of $60 to $80 per pound given in *SSC Conceptual Design*, Attachment B, p. 29.

31. Given the existence of a magnetic resonance imaging industry, however, it could be argued that further demonstration projects for superconductors are unnecessary. The roughly 2,000 imagers already in place could serve to demonstrate the usefulness of this technology.

The SSC thus appears to be a mixed blessing for the superconductor industry. It could have a drastic impact on the industry as a result of a one-time demand swing. The superconducting magnet makers may not gain much from the experience of producing 10,000 magnets but superconducting cable makers may benefit from the SSC order of superconducting cable. SSC proponents also argue that the SSC demand could attract large firms into the industry (currently, most manufacturers of superconducting magnets and cable are small). The presence of sizable federal contracts could bring in large firms that would be able to develop capacity in this growing field at government expense.

How Would the SSC Affect High-Temperature Superconductors?

The significance of this question lies in the recent discoveries of ceramic materials that exhibit superconducting properties at relatively high temperatures. At these higher temperatures, the superconductors can be cooled with liquid nitrogen instead of liquid helium; if even higher temperatures are achieved, conventional refrigeration equipment could be used. Because liquid nitrogen is much cheaper and easier to work with than liquid helium and conventional refrigeration is cheaper still, many new applications that depend on low costs for their success would be possible for superconductors. Thus, if the materials and manufacturing of these high-temperature superconductors, which are in very primitive state, can be improved, they have much greater potential than do low-temperature superconductors of being the basis of a new range of applications.

While forecasting technology is an imprecise art at best, a large part of the experience of building the SSC magnets may be irrelevant to high-temperature superconductors. The SSC magnets are currently designed around fine (6 microns in diameter) niobium-titanium filaments embedded (roughly 1 micron apart) in a copper matrix.[32] Each strand of wire has over 7,200 niobium-titanium filaments and there are over 20 strands in each cable. The process of developing the magnet coils of requisite strength from niobium-titanium has been one of metallurgical improvement, largely through the ability to make

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32. See Eric Gregory, "Advances in Superconducting Wire and Cable for the Superconducting Supercollider," *Supercurrents* (March 1988), pp. 21-24.

the superconducting filaments of a consistent diameter and spacing them precisely in the superconducting strands of wire. The high-temperature superconductors, on the other hand, have thus far been largely ceramics, requiring very different handling. Other low-temperature superconductors behave more like the ceramic high-temperature superconductors, for instance niobium-tin, but these are much more expensive and difficult to work with than niobium-titanium and so have not been widely used in commercial or particle physics applications.

The SSC Central Design Group has been conducting experiments on test magnets at Fermilab and Brookhaven National Laboratory to determine the best design and manufacturing techniques for the magnets. Manufacturers will have the opportunity to study these techniques and see which should apply to the construction of the 10,000 magnets. The experiments of the Central Design Group so far indicate that precise metallurgy, not applicable to high-temperature superconductors, will dominate the SSC magnets.[33]

The other factor limiting the transfer of technology to high-temperature superconductors is that the first likely applications of these new superconductors seem to be in electronics, where the electric current densities and mechanical strength requirements are lower. It may be decades before power applications for high-temperature superconductors become practical. By then, the technology experts who worked on SSC magnets may be long since dispersed or forgotten. Firms or researchers working on power applications of high-temperature superconductors early in the next century are more likely to look to the advanced ceramics industry for solutions to their materials problems than to the SSC.

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33. Barbara Gross Levi and Bertram Schwarzchild, "Super Collider Magnet Program Pushes Toward Prototype," *Physics Today*, vol. 41, no. 4 (April 1988), pp.17-21.

CHAPTER III

BUDGETARY RISKS IN THE SSC PROJECT

The Department of Energy currently estimates that the Superconducting Super Collider will cost $5.3 billion (in current dollars), to be spread over nine years.[1] A major aspect of Congressional concern about the SSC is whether costs will escalate substantially, if and when the SSC proceeds to actual construction.[2]

Previous construction costs for DOE accelerators have experienced substantial overruns reaching between 64 percent and 120 percent. In some instances, the costs increased simply because parts cost more than initial estimates. In other instances, research costs rose, or DOE encountered unexpected insurmountable technical problems that required an expensive redesign in one case and cancellation of a project in another. Given the risky nature of accelerator and other big science instrument design and construction, major cost increases in this program would not be unusual.

CURRENT DOE COST ESTIMATES FOR THE SSC

Table 3 presents the DOE estimate of the cost of the SSC by category of spending. DOE expects the SSC to cost a total of $4.4 billion.[3] SSC costs are dominated by technology (components, and research and development) and risk (contingency). Construction costs of the technical components ($1.5 billion) and detectors ($0.7 billion) account for 50 percent of the total project costs. If R&D ($0.3 billion), which is dominated by magnet R&D, and the portion of engineering and design accounted for by technical components are added to this equation, then technology and its development account for over 60 percent of

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[1] This does not include $80 million in research and development performed between 1984 and 1987. See Department of Energy, *Superconducting Super Collider* (April 1988), p. 27.

[2] For a recent expression of Congressional concern, see *Energy and Water Development Appropriation Bill, 1989*, Report No. 100-381, Senate Committee on Appropriations, to accompany H.R. 4567, 100:2 (1988), p. 134.

[3] Unless otherwise noted, all costs are in fiscal year 1988 dollars. The discussion of costs in this section is based on SSC Central Design Group, *Conceptual Design of the Superconducting Super Collider* (March 1986), (referred to hereafter as *SSC Conceptual Design*), Attachment D, pp. 657-702, and Department of Energy, *Superconducting Super Collider*.

TABLE 3. DOE ESTIMATE OF THE COST BREAKDOWN FOR THE SSC
(In millions of fiscal year 1988 dollars)

Category	Estimates
Construction	
Technical components	
Magnets	1,068
Cryogenics	129
Other	322
Subtotal	1,519
Conventional facilities	
Collider facilities	370
Other	244
Subtotal	614
Engineering and design	307
Management and support	205
Contingency	565
Total, construction	3,210
Detectors	719
Research and Development[a]	274
Pre-Operating	172
Total	4,375

SOURCE: Department of Energy.

NOTE: Estimates made before Congressional appropriations for fiscal year 1989.

[a] Does not include $80 million for research and development performed between 1984 and 1987.

TABLE 4. FUNDING AND COST PROFILE FOR THE SSC
(By fiscal year, in millions of current dollars)

Category	1988	1989	1990	1991	1992	1993	1994	1995	1996	Total
Funding Profile										
Total Funding	25	363	675	774	809	879	946	594	255	5,320
Cost Profile										
Construction	0	150	350	510	630	660	690	670	350	4,010
Research and Development[a]	25	68	68	46	29	20	15	16	6	293
Pre-Operating	0	0	0	0	0	17	44	76	65	202
Detectors and Computers	0	12	22	110	125	145	147	175	79	815
Total Cost	25	230	440	666	784	842	896	937	500	5,320

SOURCE: Congressional Budget Office, derived from Department of Energy budget request and construction project data sheets for fiscal year 1989.

NOTE: Estimates made before Congressional appropriations for fiscal year 1989.

a. Does not include $80 million in research and development performed between 1984 and 1987.

total project costs. Risk, as expressed in contingency costs ($0.6 billion), accounts for a further 13 percent of total costs. DOE estimates that, once completed, the SSC will cost $270 million to operate annually, including $32 million per year for upgrades in the detectors.[4]

Table 4 presents DOE's projection of the SSC funding and cost profile in current dollars. The sum over the entire period is $5.3 billion. DOE assumes that cost inflation will average roughly 6 percent for construction; inflation for R&D and other costs will average slightly more than 2 percent. Should cost inflation deviate from the DOE estimate, these projections would change. Funding and costs will increase relatively quickly once construction is authorized, reflecting the fact that a great deal of planning has already occurred.

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[4] All these estimates were made before Congressional appropriations for fiscal year 1989. Some modifications may be needed.

OVERVIEW OF BUDGETARY RISKS

There are three ways to examine the current DOE cost estimates. They can be accepted as the best possible estimates at this time (DOE analysis); they can be analyzed for internal consistency (technical analysis); and they can be compared with previous DOE cost performance (historical analysis).

According to DOE, the current estimate (see Table 5) is accurate within 10 percent, given that the site has not been selected and the final design studies have not been performed. DOE argues that if the "right" site is chosen, the cost of conventional facilities might even fall relative to the estimate, which has some uncertainty built into it. The DOE estimate can therefore be portrayed as between $3.9 billion and $4.8 billion. (DOE has not provided information on the relative accuracy of categories within the total estimate.)

TABLE 5. SSC BUDGET ESTIMATES
(In millions of fiscal year 1988 dollars)

Category	DOE Analysis[a]	Technical Analysis[b]	Historical Analysis[c]
Construction	3,210	3,210-3,480	n.a.
Research and Development[d]	274	274	n.a.
Detectors	719	890-1,175	n.a.
Pre-Operating	172	172	n.a.
Total	3,937-4,812	4,546-5,101	6,398

SOURCE: Congressional Budget Office, based on data from the Department of Energy.

NOTE: n.a. = not applicable.

[a] Current estimates by DOE, made before Congressional appropriations for fiscal year 1989.

[b] Adjusted by CBO for internal consistency.

[c] Adjusted by CBO according to previous DOE cost performance. No component-by-component analysis was made because future cost increases may not result from the same sources.

[d] Does not include $80 million in research and development performed between 1984 and 1987.

Table 5 summarizes the Congressional Budget Office's technical analysis of the major components of DOE's current estimate. As detailed below, potential detector costs may be understated in the DOE estimate by $200 million to $500 million, according to the DOE panel on detector costs. Furthermore, DOE has made assumptions about productivity gains in superconducting magnet manufacturing that may not occur. If these gains do not materialize, costs could increase by $270 million. CBO did not subject the other parts of DOE's estimate to analysis. The lower bound of the technical analysis is well within the stated range of confidence of 10 percent for the DOE estimate, while the upper bound of the technical analysis is $300 million above the range of confidence and more than $725 million above the DOE's average estimate.

The historical analysis in Table 5 simply takes the current DOE estimate and increases it by the average cost increase for the four DOE accelerators built during the 1980s. The average overall cost increase was 46 percent in real terms. Two of the accelerators did not exceed their original cost estimate, whereas two suffered from exceptionally high cost escalation. No component-by-component analysis of cost increase was made because future cost increases may not result from the same sources.

DETECTORS

The detectors are a vital part of the SSC. They will collect all the information during proton collisions in the interaction regions. All scientific results coming from the SSC will depend on the quality and scope of these detectors.[5] The detectors required by the SSC, like the accelerator itself, are large: the largest components are magnets the size of a small house.

DOE's current cost estimate for SSC detectors is $719 million, but this estimate is highly uncertain, mainly because the SSC Central Design Group has not yet specified the type and number of detectors to be used in the SSC. In 1985, the Detector Cost Model Advisory Panel of the SSC Central Design Group provided one possible configuration of detectors that could be used to evaluate the cost of the detector component of the SSC.[6]

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[5] For a discussion of types of detectors and the roles they play, see National Research Council, *Physics Through the 1990s: Elementary Particle Physics* (Washington, D.C.: National Academy Press, 1986), pp. 132-156.

When the Advisory Panel made its final recommendations, it kept a range of scientific expectations in mind, ~~providing~~ a scenario and not the final design. According to the panel, it is highly probable that the final detectors will bear little resemblance, apart from their function, to the proposed configuration of detectors, which merely provided a basis for a cost estimate.

The Advisory Panel estimated the costs using the data from detectors already in use or under construction. The panel estimated increases and decreases in component costs from the base cost of these detectors. It did not assume any economies of scale and assumed lower costs for the next generation of electronics used in the detectors. No costs were added for the moving and storage of the existing detectors that will be upgraded for the SSC.

Table 6 gives the cost breakdown for all the detectors and spectrometers evaluated by the Advisory Panel. The table provides a range of $682 million to $752 million for the total hardware cost of the detecors, depending on which combination is preferred. The panel recommends that the cost range should be widened by 15 percent on both sides to allow for the uncertainty, so the new range of the cost of hardware would be from $580 million to $865 million.

Some omitted associated costs should also be added to make the cost estimate more accurate (see Table 6). For example, the cost of R&D is not in the Advisory Panel's estimate. Since almost all new detectors and one upgrade are proposed, it is highly likely that some funds will be spent on R&D. Based on the Fermilab experience, DOE estimates that R&D costs will be $48 million. DOE maintains that conventional accounting for detectors never includes R&D costs, but this argument ignores the fact that DOE is the only U.S. organization

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6. The proposed detectors and their cost estimate are detailed in SSC Central Design Group, "Cost Estimate of Initial SSC Experimental Equipment" (June 1986), Attachments A and B.

TABLE 6. RANGE OF COST ESTIMATES FOR ONE POSSIBLE CONFIGURATION OF DETECTORS FOR THE SSC
(In millions of fiscal year 1988 dollars)

Category	Low Estimate	High Estimate
Hardware Costs		
4pi Magnetic Detector	309	356
Spectrometer for High-Energy Muons	171	186
Upgraded and Forward/Intermediate Detectors[a]	181	189
Specialized Detectors	21	21
Subtotal	682	752
Expanded Range	580[b]	865[c]
Contingency	187	187
Total, hardware costs	767	1,051
Associated Costs		
Research and Development	48	48
Off-Line Computing	76	76
Total, associated costs	124	124
Total	891	1,176

SOURCE: Configuration from Detector Cost Model Advisory Panel of the Central Design Group for the SSC. Estimates by the Congressional Budget Office, calculated from SSC Central Design Group, "Cost Estimates of Initial SSC Experimental Equipment" (June 1986), Attachment B, Appendix B, Tables 1-10, using the Department of Energy's inflation index for energy research and nuclear construction.

NOTE: Details may not add to totals because of rounding.

a. The original estimates for the detector upgrade were $96 million to $133 million. Current estimates are $80 million. The forward or intermediate detector would cost $101 million to $109 million.

b. Hardware subtotal minus 15 percent.

c. Hardware subtotal plus 15 percent.

building large detectors for accelerators and thus sets the convention. An additional $76 million for off-line computing was also estimated by the same panel.[7]

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[7] SSC Central Design Group, "Cost Estimate of Initial SSC Experimental Equipment," Attachment C.

A main consideration in the eventual cost is the contingency added to cover errors or items unintentionally missed in the estimate. The Advisory Panel recommends an average contingency cost of $187 million for the whole system.[8] DOE does not include contingency costs in its estimate, contending that they "can be absorbed by adjustments in the total scope of the experimental plan."[9]

As shown in Table 6, the modified estimate of the cost of the detectors could be as high as $1.2 billion, or as low as $900 million, barring substantial advances in detector manufacturing beyond those assumed by DOE.

DOE maintains that the Advisory Panel's estimate is overstated because the capabilities of the detectors can be adjusted to control costs: the estimate was preliminary and did not seek to provide the maximum amount of physics per detector dollar. Some cost savings should therefore be possible without seriously affecting the quality of science. On the other hand, the mid-range of $900 million to $1.2 billion is about $1 billion. Thus, DOE is asserting that over $300 million, or about 30 percent, could be saved without affecting the quality of the science.

While DOE believes that it can "manage to cost," the experience with Tevatron I suggests otherwise. In that instance, the detector costs rose from $20 million to $57 million (see below for a detailed discussion). DOE holds that the cost increase resulted from a consolidation in accounting rather than from a true increase, but this argument still suggests that original estimates may be incomplete.

SUPERCONDUCTING MAGNETS

When engineering and contingency costs are included, magnet construction costs account for $1.4 billion--over 40 percent of the SSC construction costs of $3.2 billion. As Table 7 shows, over half of this ($796 million) is in the construction of the 7,680 dipole magnets. Construction of the dipoles will pose a substantial technological chal-

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[8] The Advisory Panel actually used $175 million, which is 25 percent of the average hardware cost, rather than 25 percent of the upper and lower cost estimates. See SSC Central Design Group, "Cost Estimate of Initial SSC Experimental Equipment," p. 93. CBO then converted this number to 1988 dollars, using the DOE's inflation index for energy research and nuclear construction.

[9] SSC Central Design Group, "Cost Estimate of Initial SSC Experimental Equipment," p. 8.

TABLE 7. DOE ESTIMATE OF SUPERCONDUCTING MAGNET COSTS (In millions of fiscal year 1988 dollars)

Category	Estimates
Construction	
Tooling	60
Dipole magnets	
Magnet coils	389
Yoke and helium containment	122
Cryostat assembly	122
Other	162
Subtotal	796
Quadrupole magnets	
Magnet coils	15
Yoke and helium containment	5
Cryostat assembly	9
Other	13
Subtotal	42
Correction magnets	83
Interaction region magnets	42
Installation and alignment	45
Total, construction	1,068
Engineering, Design, and Inspection	123
Contingency	217
Total	1,407

SOURCE: Congressional Budget Office, calculated from SSC Central Design Group, *Conceptual Design of the Superconducting Super Collider* (March 1986), pp. 696-699 and Attachment D, Appendix B, using the Department of Energy's inflation index for energy research and nuclear construction.

NOTE: Details may not add to totals because of rounding.

lenge, since these magnets would be longer and more powerful than most existing superconducting magnets. In fact, DOE has encountered many problems in its attempts to produce these magnets in a research environment.

The costs of the superconducting magnets are sensitive to many assumptions. Superconducting magnets have never been manufactured on this scale. While DOE has attempted to extrapolate from its Fermilab experience, it has made a series of assumptions about improvements in manufacturing capabilities and technology that may prove to be optimistic. DOE's own figures suggest that, should these improvements fail to materialize, costs could rise by over $270 million for several reasons.

- The cost of labor for assembly and fabrication is based on as yet unrealized automation of many production steps. If these improvements in productivity do not occur, then a DOE analysis suggests the superconducting magnets may cost $88 million more than projected. Similarly, if productivity is not increased, extra facilities, requiring extra tooling, may be required to meet schedules. DOE figures suggest these extra facilities would add $33 million to costs.

- The allowance for rejects is small, assuming that only 2 percent of the magnet coils and 0.5 percent of the completed magnets are rejected as unusable. The magnet cost also assumes that only 5 percent of the superconducting cable and just 1 percent of all other materials purchased are not used, either through excess procurement or wastage.[10]

- While there is now substantial excess capacity in the fabrication of high-purity niobium-titanium alloy and rod that will be used to make the superconducting cable, the bulk of current spare capacity is in one facility in one company. The DOE estimate assumes the supplier will be able to achieve economies in internal processing. Without these economies, material costs could rise by $32 million.

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[10] *SSC Conceptual Design*, Attachment D, Appendix B, pp. 492 and 493. The last assumption--1 percent of all other materials wasted--seems especially low.

There is also the question of how easily the Fermilab experience will transfer to the industrial manufacture of the superconducting magnets. Tevatron I magnets were built under the supervision of highly trained and motivated technicians. Industry's labor force may be less familiar with the magnets specifically and accelerators in general. This transfer of an institutional setting to industry lowers the confidence in DOE's estimates, although admittedly no other organization is as experienced in estimating magnet construction costs.

CONVENTIONAL FACILITIES

DOE currently estimates that the conventional facilities for the SSC will cost $860 million. In order to contain hazardous muon radiation emanating from the magnet rings, the SSC will require the construction of a tunnel in which to place the rings. Other more conventional buildings will also be needed. The tunnel and related collider facilities (including contingency costs) account for roughly half of the $860 million. Site and infrastructure preparation account for slightly more than $100 million. Table 8 presents the breakdown of DOE's cost estimate.

The site for the SSC has not yet been chosen. Consequently, the qualities of the site, which can add substantially to costs, are unknown and are among the largest budgetary risks posed by the SSC. The main cost risk is the large tunnel. For instance, depending on the site, the tunnel may be near the surface or between 200 and 400 feet underground.[11] Of the hypothetical sites used by DOE for estimating purposes, the deepest was 150 feet below ground.

The Central Design Group made three estimates of collider and experimental facility costs.[12] Site A was a hypothetical tunnel 50 feet underground and would require soft ground tunneling with a tunnel boring machine. Water might be encountered at this depth. Site B

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[11] See National Research Council, *Siting the Superconducting Super Collider* (Washington, D.C.: National Academy Press, 1988), pp. 26-37.

[12] This discussion is based on *SSC Conceptual Design*, pp. 659-661.

TABLE 8. DOE ESTIMATE OF THE COST OF CONVENTIONAL FACILITIES (In millions of fiscal year 1988 dollars)

Category	Estimates
Construction	
Site and infrastructure	91
Campus area	46
Injector facilities	42
Collider facilities	
North arc	130
South arc	146
East cluster	34
West cluster	43
Surface buildings	2
Cryogenic buildings	15
Subtotal	370
Experimental facilities	66
Total, construction	615
Engineering, design, and inspection	98
Contingency	
Site and infrastructure	18
Campus area	9
Injector facilities	8
Collider facilities	92
Experimental facilities	20
Total, contingency costs	148
Total	861

SOURCE: Congressional Budget Office, calculated from SSC Central Design Group, *Conceptual Design of the Superconducting Super Collider* (March 1986), pp. 678-693, using the Department of Energy's inflation index for energy research and nuclear construction.

NOTE: Details may not add to totals because of rounding.

was 150 feet underground in predominantly solid rock below the water table using a tunnel boring machine. Site C was near the surface using surface excavation techniques. To obtain their cost estimate, the Central Design Group averaged the costs for the three sites. Thus, while the actual estimates for the collider facilities ranged from $328 million to $410 million, the cost estimates used an average figure of $370 million. This means that $40 million of the $92 million in contingency costs allocated for collider facilities might be used by the site selection. Indeed, of the sites that could be selected, only one site would use cheaper "cut-and-cover" techniques, and several sites are well below the depth of 150 feet.

On the other hand, DOE argues that the geology and tunneling criterion has the highest weight of the six technical criteria being used by the site selection panel and that cost is a consideration in the overall evaluation. Consequently, they feel that the chosen site is unlikely to be a high-cost site and that, as a result, costs may actually be lower than estimated.

SCHEDULE

Accelerators in the United States have often taken longer to build than originally planned. The Energy Saver slipped two years, and the Tevatron I slipped three to four years. Other countries have had similar experiences: the latest accelerator of the European Organization for Nuclear Research (CERN), the Large Electron Positron collider, was supposed to be finished in 1988, but the estimated date of completion is now July 1989.

In the case of the SSC, *SSC Conceptual Design* includes a construction schedule of eight years. A slip in ~~one~~ part of the schedule may delay other parts, increasing costs. The schedule includes no time for legal and other delays, which often occur around controversial construction projects, both public and private.

Conventional Facilities

In addition to not accounting for legal or other outside delays, the schedule is already tight. The DOE's panel reviewing the conceptual design for conventional facilities concluded that "examinations of the proposed schedules show them to be very tight, but adequately coordinated with schedules for technical systems installation and with the assumed funding profile. Changes in either will have major effects on the schedules and probably on the costs of conventional facilities."[13]

Superconducting Magnets

The schedule for the manufacture of the magnets is also tight. The current schedule has mass production occurring between 1992 and 1996, after periods of transferring technology and certifying and selecting vendors. There are to be 10 production lines each producing one magnet per day, a total of between 2,000 and 2,500 per year. This rate is three to four times the current production rate in the industry. The rate permits very little slippage, and assumes substantial automation and other improvements in the manufacture of the superconducting cable and the fabrication of the superconducting magnets. DOE argues that if cable and magnet production falls behind schedule, the overall rate could be restored by additional production lines; however, such additions would increase costs.

Thus, on the one hand, if the manufacturing technology fails to progress as assumed, the SSC superconducting magnets may be delivered at a much slower rate than called for by the plan. On the other hand, without knowing the exact site geology, it is quite possible that the tunnel might not be ready to receive the magnets, should they be produced on schedule.

INCREASES IN CONSTRUCTION COSTS OF PREVIOUS ACCELERATORS

Cost escalation has been a consistent problem with DOE particle accelerators in the recent past. Some have exceeded initial estimates, while others kept their construction costs within estimates by subsidizing them from other budget areas.[14] In one case, such large technical problems were encountered that the program was terminated. On the other hand, DOE argues that the focus on several recent cases ignores several decades of record timeliness and cost efficiency. CBO did not analyze the performance of the 1960s. Of the six projects begun since 1970 in the United States, however, three have either gone over budget or been terminated. Those three are the accelerators most similar in technology to the SSC.

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[13] Department of Energy, *Report of the DOE Review Committee on the Conceptual Design of the Superconducting Super Collider* (May 1986), p. 6-2.

Four major particle accelerators have been completed since 1980: the Energy Saver and Tevatron I and II at Fermilab, and the Stanford Linear Collider. The Energy Saver and Tevatron I experienced substantial cost increases, while Tevatron II, a much more straightforward project, was on budget.[15] There has been no systematic analysis of the Stanford Linear Collider, but it is CBO's understanding that it experienced no major cost increases, although money may have been transferred from operating funds to cover increased construction costs.[16] These histories indicate three potential problems with the current DOE cost estimate for the SSC:

- Individual items may simply cost more to procure than was originally thought. This was true of the Energy Saver, which was built during a period of high inflation.

- Technical problems may arise where none appears at present. The Tevatron I, for example, experienced substantial increases in costs because DOE ran into unexpected technical problems.

- Progress in particle physics between now and the end of construction may require redefinition of the project. For both the Energy Saver and Tevatron I, more research was needed than DOE scientists had originally thought.

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[14] The sample of recent particle accelerators ~~is~~ very small (five attempted, one canceled) and the confidence in any conclusion based on this sample must be considered low. Given all the factors affecting accelerator costs, however, particularly technical risks, initial accelerator cost estimates are very uncertain.

[15] For an analysis of Tevatron II, as well as the other accelerators, see General Accounting Office, *Information on DOE Accelerators Should Be Better Disclosed in the Budget* (April 1986), p. 45. For DOE comments on GAO estimates, see p. 83.

[16] Solving the recent problems at the Stanford Linear Collider may require some additional funds, which are planned to come out of operating funds.

The Energy Saver

The Energy Saver, also known as the Energy Doubler, is the name given to the addition of a ring of superconducting magnets to the original Fermilab proton synchrotron.[17] The addition doubled the energy beam of the synchrotron to 800 billion electron volts while reducing electricity consumption.

The Energy Saver was the idea of the physicists building the Fermilab proton synchrotron in 1971, and they began research while working on the synchrotron. In 1979, after eight years of research, the Congress approved the Energy Saver as a construction project. (The authorization did not include R&D and other development costs.) Table 9 compares the initial estimate with the final cost. (For a comparison of current dollar cost increases, see Appendix C.) The largest cost increase was in the R&D necessary to complete construction. In 1979, DOE estimated that R&D for the project would total $50.2 million, but by 1982, R&D costs had increased to $103.7 million. Construction costs had also increased, and the total costs rose from the 1979 DOE estimate of $113.4 million to the final 1982 estimate of $186.1 million, a 64 percent cost increase. Scheduled completion had also slipped about two years.

Tevatron I

Even before completion, physicists at Fermilab envisioned additions to the Energy Saver. The Tevatron I design modified existing Fermilab facilities in three ways: it added an antiproton cooling and accumulation system, modified the Energy Saver superconducting accelerator ring so that it could be used as a storage ring for colliding beams or protons and antiprotons, and provided two new experimental areas for simultaneous particle physics experiments.

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[17] The discussion of the history of the Energy Saver is largely based on Lillian Hoddeson, "The First Large-Scale Application of Superconductivity: The Fermilab Energy Doubler, 1972-1983," *Historical Studies in the Physical and Biological Sciences*, vol. 18, part 1 (1988), pp. 25-54.

TABLE 9. CHANGES IN THE COST OF ACCELERATORS
(In millions of fiscal year 1988 dollars)

Category	Initial Estimated Cost[a]	Final Estimated Cost
Energy Saver		
Facility	55.1	67.2
Research and Development	50.2	103.7
Other	8.1	15.3
Total	113.4	186.1
Tevatron I		
Facility	47.4	93.7
Research and Development	16.9	57.9
Other[b]	7.8	0.0
Detector	24.3	61.5
Total	96.4	213.1

SOURCE: Congressional Budget Office, calculated from Department of Energy budget requests for fiscal years 1979, 1981, 1982, and 1987. Details on the costs of detectors from Fermilab budget activity reports, 1981-1987. Numbers adjusted for inflation using the gross national product deflator.

a. Calculated from DOE's fiscal year 1979 estimate for the Energy Saver and DOE's fiscal year 1981 budget request for the Tevatron I.

b. Items in other categories were reclassified into other parts of the Tevatron I budget.

When the Congress authorized the project in fiscal year 1981, Tevatron I was to cost $47 million and to be completed by the third quarter of 1983. In addition, R&D costs were estimated to be $16.9 million and ancillary costs to be $7.8 million. The detectors were forecasted to cost an additional $24.3 million, of which the DOE share would be $12.2 million, the rest coming from international sources.[18] The project costs were to total $96.4 million, of which the United States was to pay all but $9.4 million. By the time the project was completed, the Tevatron I cost the United States $213.1 million, a 121 percent cost increase, and was between three and four years late.

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[18] An estimate of detector costs appeared in DOE's 1982 budget request. The 1981 budget request had no detector cost estimate and merely stated that the detector was to be paid out of capital equipment costs. The National Science Foundation was also to contribute to the detector.

Table 9 compares the 1981 Budget Request with the final project costs. (For a comparison of detailed current-dollar cost increases, see Appendix C.)

In the course of constructing Tevatron I, DOE decided to change the technology used to produce antiprotons.[19] DOE had encountered substantial technical obstacles. CERN, however, had discovered a better way to produce and control antiprotons. Consequently, DOE decided to redesign the entire antiproton production and control mechanism. Whereas previously the Tevatron I designers had hoped to use many of the existing Fermilab facilities, the new design required the construction of completely new facilities. The redesign and the increased cost associated with it caused a delay of two years.

Other Big Projects

Particle physics is not unique in suffering from cost escalation: big instruments and large construction projects in other areas often suffer the same fate. The National Aeronautics and Space Administration (NASA), which, like DOE, builds big scientific instruments, provides several examples of cost escalation. One such example is the Hubble Space Telescope, which is the first of four orbiting astronomy observatories.[20] CBO's analysis of the program indicated that between 1978 and 1988, the cost estimate rose 135 percent in real terms. While part of the cost increase is the result of the shuttle Challenger accident, by 1982 the costs had already gone up by almost 30 percent.

In its study of defense acquisition, the President's Commission on Defense Management studied cost growth in major projects in both the private and public sectors, including defense and nondefense applications. The two categories that most aptly describe the SSC--instruments and large construction projects--both experienced, on average, cost increases of over 100 percent.[21]

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[19] This discussion is based on a letter dated June 16, 1982, to Senator James A. McClure, Chairman, Committee on Energy and Natural Resources from Alvin W. Trivelpiece, Director, Office of Energy Research, Department of Energy.

[20] Congressional Budget Office, *The NASA Program in the 1990s and Beyond* (May 1988), p. 42. Other NASA projects that are suffering substantial cost increases include the Ulysses mission to the sun, the Galileo mission to Jupiter, the Mars Observer mission, and the Magellan mission to Venus.

Applicability of Past Experience to the SSC

Past experience may not necessarily be a perfect guide to how the construction of the SSC might develop. In many ways, the SSC is an extension of the Energy Saver and Tevatron I technology to higher energy levels. The technical difficulties encountered by those projects may benefit the SSC by allowing it to avoid the same problems. The superconducting magnet technology is now more mature than it was when the Energy Saver was first contemplated 17 years ago. Furthermore, Tevatron II and the Stanford Linear Collider show that accelerators can be built close to their estimated cost. On the other hand, Tevatron II was a much less complex project than the others.

These earlier accelerators were also authorized much earlier in their design cycle than the SSC would be. A substantial portion of the cost escalation in these projects occurred during the R&D phase, after they had been authorized but before actual construction began. Proponents of the SSC claim that because the design of the SSC has been thoroughly analyzed and the cost estimates have remained stable for several years, there is less chance of major design changes with their consequent cost increases. In addition, advances in CERN accelerator technology were also a substantial factor in the need to redesign the earlier projects. On the other hand, the R&D phase for SSC detectors has hardly begun, so there might be substantial cost increases in that phase. The superconducting magnets are also still in the research phase. Furthermore, although CERN accelerator technology is unlikely to influence the design of the SSC because the SSC is much more powerful, it is still possible that high-energy physics might progress enough to require substantial redesign of the SSC, as in the case of the Energy Saver and Tevatron I.

The other uncertainty in attempting to use these project histories to determine if SSC costs will escalate is that the SSC budget is much larger than that of the previous accelerators. Both the Energy Saver and Tevatron I eventually cost $186 million and $213 million, respectively. The Energy Saver's 64 percent cost overrun (on the original estimate of $113 million) was $73 million. Thus, while large relative to project costs, relative to the budget for the SSC, these overruns were small. Similarly, for both the Energy Saver and Tevatron I, one-third to one-half of the cost escalation occurred in component acquisition, not R&D costs.[22] Since the SSC will need more components, there might be a greater risk of cost inflation.

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[21] President's Blue Ribbon Commission on Defense Management, *A Formula for Action: A Report to the President on Defense Acquisition* (April 1986), p. 38.

SHARING THE COST OF THE SSC

DOE assumes that funds from nonfederal sources will help defray the costs of the SSC, beginning in 1991. These assumptions have been called into question even by proponents of the SSC as overly optimistic. The DOE budget request for 1989 assumes $1.8 billion in nonfederal funds, roughly one-third of project costs. The most commonly discussed sources for these funds are the state in which the SSC is located and the international community.

State Contributions

The SSC proposal requires substantial contributions from states, mainly in land and infrastructure.[23] The finalist states have expressed their willingness to contribute to the construction of the SSC through these avenues. In addition, some proposals would have the states contribute funds for the construction. Texas and Illinois have both approved major bond issues for this purpose, should the SSC be located in their states.

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[22] In the case of the Energy Saver, the magnet cost increase was partially offset by a fall in the cost of refrigeration that occurred because Fermilab was able to acquire used equipment. This is unlikely to occur with the SSC. For details of Energy Saver and Tevatron I cost overruns, see Appendix C. For more on Energy Saver construction, see Hoddeson, "The First Large-Scale Application of Superconductivity."

[23] DOE's budget request assumes no costs in land acquisition and assumes the state will pay for substantial portions of the infrastructure, although DOE often includes the land and other excluded contributions in its assessment of nonfederal contributions.

While the competition among the states has been viewed as a fight for local benefits, there are legitimate reasons why states might be expected to contribute, since regional benefits will flow from the SSC. The presence of science and technology centers can aid a state in the process of economic development. High-technology industries, for instance, feed upon each other's growth.[24] Science-based employment can also counterbalance some cyclical fluctuations in traditional manufacturing and commodity-based employment. Because of the local public good benefits, state contributions to the construction, beyond providing the infrastructure, might be appropriate. On the other hand, the Congress instructed DOE not to consider financial contributions from states in its site selection deliberations in order to avoid putting smaller states at a disadvantage and turning the process into an auction. In addition, special agreements might have to be made with the selected state to incorporate its donations.

Foreign Contributions

Both opponents and proponents of the SSC agree that the federal government should seek international funding. International participation could come in the form of money or in-kind contributions, the latter being the most common. The items that have raised the most interest in international circles are the detectors and the superconducting magnets--the detectors would require substantial foreign contributions, while the magnets would reduce the potential of technology spinoffs for the United States.

Financial contributions from foreign sources of the magnitude assumed by DOE seem unlikely at this time. According to DOE, the European Community as a whole had a high-energy physics budget of $1.0 billion in 1988. CERN accounted for $534 million, or roughly half of this. CERN members are currently discussing another accelerator--the Large Hadron Collider--which they feel covers much of the same energy range as the SSC, but at a lower cost. According to DOE, in 1987, Japan had a particle physics budget of roughly $210 million per

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24. For a discussion of histories and prospects for such development, see Peter Hall and Ann Markusen, eds., *Silicon Landscapes* (Boston: Allen and Unwin, 1985).

year.[25] Lastly, Canada spends little on high-energy physics: estimates range between $10 million and $50 million per year. Since all these sources have commitments of their own, it is unlikely they will have the funds to make contributions to the SSC that are as large as DOE estimates. On the other hand, non-CERN sources have contributed $100 million for CERN's latest detector, two-thirds of which came from the United States.

If the European Community forgoes building its next-generation proton accelerator, currently the Large Hadron Collider at CERN, then its members may have funds to spare for U.S. high-energy physics experiments. However, such a situation seems unlikely. As its next director general, CERN has chosen Carlo Rubbia, the person most closely associated with the Large Hadron Collider, and the European Community seems committed to CERN, although it is quite possible that the process of building the Large Hadron Collider may be stretched out longer than its proponents might desire.

There are sources of European and Japanese funds outside the particle physics programs, however. In-kind contributions of detectors, superconducting magnets, and other high-technology components might be viewed by foreign countries as a way of both stimulating their high-technology industries and obtaining a foothold in U.S. markets. The United States may wish to protect it own manufacturers from such competition. So far, however, only European firms have built powerful superconducting magnets in an industrial setting. No U.S. superconducting magnet firm has built an accelerator magnet this powerful, and DOE has no experience building superconducting magnets industrially. If the Congress puts "buy-national" restrictions on SSC appropriations, it may be forgoing the experience of firms that have actually built these powerful accelerator superconducting magnets and costs could be higher.[26] Buy-national provisions may also make it impossible to obtain international contri-

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25. Department of Energy, *Report of the HEPAP Subpanel on Future Modes of Experimental Research in High-Energy Physics* (July 1988), p. 59. The analysis assumes 1.49 Swiss francs and 148 Japanese yen to the U.S. dollar, respectively.

26. Such restrictions may also violate the Procurement Protocols of the General Agreement on Tariffs and Trade (GATT). See Congressional Budget Office, *The GATT Negotiations and U.S. Trade Policy* (June 1987). For a chronology of foreign experience building accelerator superconducting magnets, see *Superconducting Super Collider*, Hearings before the House Committee on Science, Space, and Technology, 100:1 (April 7-9, 1987), pp. 458-462.

butions for the construction phase. Given the stated intent of Europe and Japan of pursuing accelerator technologies that include superconducting magnets, U.S. firms are in any case unlikely to have monopolies on technology for the fabrication of superconducting magnets.

The Italian government contributed superconducting magnets, made by an Italian company, to the HERA project in West Germany. DOE claims the Italian government may be willing to make a similar gift to the SSC project. But only $100 million would be saved if the Italian government donated as much as 10 percent of the superconducting magnets. At this juncture, DOE has yet to produce other evidence to support the claim that foreign and state donations are likely to cover $1.8 billion of SSC costs.

CHAPTER IV

CONGRESSIONAL OPTIONS

The next Congress will decide whether to fund the construction of the Superconducting Super Collider (SSC), defer the decision, or cancel the program. The Congress could simply defer the decision on actual construction while continuing research, as it has in the past. If the Congress cancels the SSC, options for a substitute facility include joining the European Organization for Nuclear Research (CERN) in the construction of their next accelerator, the Large Hadron Collider, in Geneva. Alternatively, the Congress could fund additional research leading to the construction of an electron-positron linear collider in the United States. Lastly, the Congress could postpone the construction of the SSC until the development of suitable high-temperature superconducting magnets. The various options have different degrees of risks and likely benefits associated with them.

Table 10 compares the four accelerators discussed in this chapter according to their cost, completion date, mass reach, and design risk. The cost is the likely federal cost. The completion date is when the instrument is intended to become available for high-energy physics. Mass reach is the mass level of the interactions or particles. (Only a fraction of the total energy from proton collisions can be used by science. For example, while the proton collisions in the SSC will have a total energy of 40 trillion electron volts, the mass reach is only 3 trillion to 4 trillion electron volts. With electron-positron collisions, virtually all the particle beam energy is available for interactions of scientific interest.) In Table 10, mass reach is synonymous for the scientific potential of the instrument.[1] The design risk is a qualitative assessment comparing the current state of accelerator technology with the eventual ability of the instrument to perform as originally planned. The primary risk is not that the machine will not work, but rather that it will be less powerful or useful as a scientific instrument than its designers intended.

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[1] Physicists convert mass into terms of energy using Einstein's equation: energy equals mass times the velocity of light squared.

The SSC is the most scientifically capable machine, in terms of its energy level and accelerator technology, but it is also by far the most expensive of the near-term options. The Congress will therefore have to decide whether the added scientific value and the lower design risk are worth the additional $3 billion to $4 billion they are likely to cost U.S. taxpayers.

Of the cost estimates, that of the SSC is most reliable: the others include estimates based on technology that is not yet developed. The SSC estimate is based on the Congressional Budget Office's technical analysis of the Department of Energy's estimate. The other estimates are constructions based on reasonable assumptions, which are discussed below.

The phenomena physicists seek to explain with the next generation of accelerators occur at mass reach levels of up to roughly 1 tril-

TABLE 10. COMPARISON OF FUTURE ACCELERATORS

	Superconducting Super Collider	Large Hadron Collider	Electron-Positron Collider	SSC with High-Temperature Superconductors
Estimated Cost to the United States (Billions of fiscal year 1988 dollars)	4.5-5.1	0.6-1.0	1-2	4.4
Completion Date	Late 1990s	Late 1990s	Late 1990s	After 2010
Mass Reach (Trillions of electron volts)[a]	3-4	1.0-1.5	1	3-4
Design Risk[b]	lowest	high	high	highest

SOURCE: Congressional Budget Office.

a. Mass reach is related to energy and refers here to the scientific potential of each instrument.

b. Design risk is a qualitative assessment of the possibility that the accelerator will be less powerful or useful than originally planned.

lion electron volts. (By way of perspective, Tevatron I, currently the world's most powerful accelerator, has a mass reach of roughly 0.3 trillion electron volts.) Both the SSC and the Large Hadron Collider have more than enough energy to study these phenomena. All machines can reach that level, but the electron-positron linear collider may be unable to explore completely phenomena at the upper reaches of the energy range. However, an electron-positron linear collider, if built, stands a good chance of making substantial contributions to high-energy physics.

As a scientific instrument, the SSC seems to have the lowest level of risk of any of the alternatives, although the SSC is far from riskless. The Large Hadron Collider will require superconducting magnets of unusual design with strengths that have not yet been achieved. Similarly, electron-positron linear colliders need substantial additional research before they become a reality. On the other hand, the SSC has already benefited from $105 million in magnet and other research and development, and will need another $250 million. It is difficult to say that electron-positron linear collider technology would not make substantial progress with $250 million for R&D.

DEFER THE DECISION

The Congress has already postponed the decision to build the SSC for fiscal year 1989. Recently, Frank Press, President of the National Academy of Sciences, suggested that actual construction might be deferred while continuing magnet research until the current budget conflict is resolved.[2] If the Congress chooses this route, current research on alternative accelerator technology would presumably continue and might be increased. CERN would probably continue research on the Large Hadron Collider. If current research efforts come to fruition during the deferral period, the Congress might have more reliable information about the various options than at present. Delaying the funding for construction is not without cost, however.

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[2] Frank Press, "Dilemma of the Golden Age" (address to members, One Hundred and Twenty-Fifth Annual Meeting of the National Academy of Sciences, April 26, 1988). For additional comments, see Barbara Culliton, "Science Budget Squeeze and the Zero Sum Game," *Science* (May 6, 1988), p. 713.

This section discusses the risks and benefits of deferring the decision on whether to fund the SSC or one of the alternative projects.

Risks and Benefits to Science

The principal scientific benefit of deferring the decision is that the Congress can keep all its options open during this time of technological uncertainty about improvements in accelerator design: the technology for the Large Hadron Collider, and especially for the electron-positron linear collider, may make substantial progress during the next 18 to 36 months, lowering the design risk associated with these instruments. It might then be possible to advance high-energy physics with instruments that are less costly than the SSC while maintaining an acceptable level of risk.

Delaying the SSC, however, may disrupt other high-energy physics research, since the SSC will dominate the high-energy physics budget: no other major new projects can be undertaken while it is under construction. As discussed below, the advance of accelerator technology depends on being able to build new types of particle accelerators, which might be able to explore higher energy regions at lower costs. Decisions regarding these new projects could be made in the 1990s. If SSC construction is still absorbing a major portion of high-energy physics funds, these decisions may have to be postponed.

Lastly, in the event the Congress ultimately builds the SSC, deferral will have slowed the pace of advancement in high-energy physics by causing a later delivery date. Two new accelerators, however--the Stanford Linear Collider and Tevatron I--have enough scientific capacity to occupy physicists until the late 1990s. Even if the SSC is delayed for 18 to 36 months, it would be hard to argue that this delay would have a lasting impact on U.S. high-energy physics, especially if CERN is also slow in approving the Large Hadron Collider.

Risks and Benefits to Technology

One point in support of deferment is that benefits are already flowing from the SSC's superconducting magnet research program to industry. More research in this area is likely to produce additional advances for both the SSC and the superconducting magnet industry. At this point, only two of the eight prototype dipole magnets built by DOE have been even partially successful. Allowing more time to improve both the magnets and their manufacturing process is likely to both increase the possibility of industrial applications of the technology and decrease the design risk of the SSC.

On the other hand, DOE maintains that it already has an established technology-transfer program. Furthermore, full-scale manufacture of the magnets is scheduled to begin only after the process has been tested in an industrial setting, which should eliminate most of the design risk involved.

Budgetary Risks and Benefits

If the decision is postponed, short-term federal spending would be reduced; costly construction would be deferred until later. On the other hand, if the SSC is never to be built, it would be better to cancel it sooner rather than later: deferral, in this case, would only commit valuable resources to a wasted task.

Other Risks

The Executive and Legislative branches of government may not be able to agree on a solution for budget shortfalls in the near term. Delaying funding may leave the SSC unbuilt for years, during which time several factors could change. The SSC team could begin to drift apart as members commit themselves to projects with higher chances of being funded; technology could move forward, requiring the redesign of the SSC and further delays; and the costs of many components may rise, increasing total project costs.

BUILD THE SUPERCONDUCTING SUPER COLLIDER

Construction of the SSC would start within two years of a Congressional decision. The first two years would be spent largely on preconstruction planning. If everything went according to plan, the facility would become available for science six to seven years after that--sometime around 1997, if approved in 1989. The major risks and benefits involved in this project are scientific and technological; risks are also associated with the instrument's components, possible cost escalation, and the schedule itself.

Risks and Benefits to Science

The principal scientific benefit of building the SSC is that, barring schedule delays, it is the option that will set the most rapid pace of any of the alternatives in terms of providing access to high energy levels and hence to potential scientific discoveries. There are time and money trade-offs: how fast does the Congress want high-energy physics to proceed and how much is the Congress willing to pay to speed up discovery rates? The high-energy physics community is almost unanimous in its desire to set a rapid pace for construction. On the other hand, the U.S. high-energy physics community is unlikely to stagnate, and may indeed continue to flourish, even if the pace of construction is slower.

By the time the SSC is operational, the current generation of accelerators will have been in place for almost a decade and thus may have exhausted the major questions at the relevant energy levels. The SSC is also powerful enough to answer most of the "next step" questions in high-energy physics. Consequently, early use of the instrument means more time for high-energy physics. This continuity of effort may ensure that the expertise and scientific teamwork gained on other projects will not be dissipated by a gap in employment for the scientists involved.

There is, however, the risk that the large increases in the science budget needed to pay for the SSC may cause neglect in other basic science areas, either directly or by preempting growth. (This concern will be very large with regard to other physics research, especially in high-energy physics.) Proponents of the SSC, however, contend that the Congress rarely makes budgetary trade-offs among science projects, evaluating each on its own merits. They hold that science grows as one and that increases in one science agency's budget do not seem to preempt growth in other areas of science research.

Even if other sciences are provided for, the opportunity costs of this investment are quite high. As noted above, the SSC will cost U.S. taxpayers $3 billion to $4 billion more than collaborating with European countries on a joint accelerator or building a less powerful machine alone. Both of these instruments are more modest and may be more risky technically, but they are likely to accomplish many of the same objectives as the SSC. The issue is whether the experiments that can be performed only on the SSC justify the additional costs to U.S. taxpayers.

Risks and Benefits to Technology

Actual construction of the superconducting magnets may improve the low-temperature superconductor manufacturing technology enough to apply it to other uses. The SSC will encourage substantial automation and other techniques that enhance the production of superconducting cable and magnets. If there are new uses for low-temperature superconductors where cost is an issue, the industry may well move beyond its traditional markets in medical instruments and research. At present, there do not seem to be many new uses of this type.

At least part of the reason that low-temperature superconductors have not diffused throughout the economy is the lack of personnel trained to work with these low temperatures. The SSC will increase the size of the industry at least temporarily and trained personnel will carry their experience to other parts of the economy. On the other hand, given the growing experience of engineers and others in the business of magnetic resonance imaging equipment, which uses superconducting magnets, it is difficult to estimate how much the SSC will add to this experience.

A major technological risk is that the construction of the SSC will produce disruptive fluctuations in the low-temperature superconductor market. This effect would be magnified if no new sources of demand for superconducting magnets appeared and if SSC requirements had increased the cost of superconducting magnets to magnetic resonance imaging equipment and other users during its construction phase. The SSC may create mixed effects: it may mature production technology but provide excess demand and, in the short run, higher prices. Moreover, should the recently discovered high-temperature superconductors enjoy some technological breakthrough to ensure their early adoption, the low-temperature superconductors may not have a chance to move substantially beyond their current markets.

Budgetary Risks

As discussed in Chapter III, the SSC may cost more than estimated, even including contingency costs. Should there be a significant cost overrun, the SSC could consume more science resources than its proponents intend. While there is an allowance of 20 percent for contingency costs, many major conventional construction projects have exceeded their initial projected costs by more than 20 percent. Unexpected delays resulting from unforeseen factors--ranging from lengthy lawsuits by affected citizens to labor strikes--could add substantially to costs. Furthermore, it would be difficult to terminate such a large project should costs begin escalating out of control.

Once the SSC is built, it will raise other budgetary questions. If the SSC is located anywhere but Illinois, it will pose the question of what to do about the Fermi National Laboratory for Accelerator Research. Fermilab's budget for 1989 was $188 million and its central mission is high-energy physics. The advent of the SSC will mean that much of Fermilab's capabilities may no longer be at the frontier of high-energy physics, although other disciplines within physics might be able to make use of the facility.

Design Risks

Although the SSC is being built using mature accelerator technology, its design will test the limits of that technology. Accelerators require that all their parts work to the optimum and do so together, and the superconducting magnets or other components may not function together as designed. This risk is much lower, however, for the SSC than for any of the other accelerator designs discussed in the rest of this chapter.

So far, research for the SSC's superconducting magnets has been slow. The SSC Central Design Group has produced only eight full-size (17-meter) dipole magnets, of which only two worked. The first was a slightly modified version of the planned production magnet, calling into question its relevance to the final product, and the second did not achieve its design strength the first time it was powered up. At full power, the SSC would be running these magnets at 95 percent of their capacity. In addition, The SSC Central Design Group has yet to test how the magnets perform when they are linked. Nevertheless, DOE maintains that these two magnets, plus the many successful model magnets built to scale, constitute a "proof of principle" of their design.

Any persistent problems with the magnets could have two consequences. First, the installation of the magnets will be much lengthier as each dipole magnet will be have to be "trained" (cooled and brought up to power several times before the magnet attains its designed rating). If each of the 7,680 dipole magnets has just two such training sessions, it would add several thousand hours to the installation of the magnets. (This problem would not be unique: DOE had to train the Tevatron I magnets.)

The second consequence is more serious: with only a 5 percent margin in the capacity of its magnets, the SSC may be less powerful than originally thought. Despite the best efforts at precision in manufacture, the strength of superconducting magnets varies, and some magnets are likely to be below the specifications necessary to produce a proton beam of 20 trillion electron volts. The weaker magnets will reduce the overall energy and mass reach levels of the SSC. Tevatron I experienced similar problems: originally designed to produce beams of 1 trillion electron volts, Tevatron at first produced beams of only 800 billion electron volts. Only after many magnets had been replaced was the accelerator able to operate regularly with beams of 900 billion electron volts. The lack of spare capacity in the SSC's magnets may force DOE either to accept a less powerful machine, or to engage in an expensive magnet replacement program after the SSC is completed, or both.

JOIN CERN IN BUILDING THE LARGE HADRON COLLIDER

Herwig Schopper, the Director General of CERN, in his testimony before the U.S. Congress, invited the United States to join CERN in the process of planning and building the Large Hadron Collider

(LHC), which may become CERN's next-generation accelerator.[3] This would be a new step in international cooperation. While many countries often participate in individual experiments, international cooperation in the construction of accelerators is limited, except in the case of CERN, which is a multinational consortium. The LHC is not necessarily a replacement for the SSC: some view it as an intermediate step. The energy levels are roughly one-third of the magnitude of those intended for the SSC, meaning that fewer phenomena could be studied. But because it uses existing facilities, the cost is also estimated to be less than that of the SSC.

The LHC would be built by adding new equipment to CERN's Large Electron Positron collider, which will soon be completed.[4] The Large Electron Positron collider's designers provided for additional capacity for the day when higher energies would be desired. According to advocates of the LHC, if a ring of superconducting magnets is placed in the Large Electron Positron collider tunnel, it would have the capacity to accommodate proton-proton collisions at an energy level of 14 trillion to 16 trillion electron volts, providing a mass reach of 1 trillion to 1.5 trillion electron volts. Since the mass reach would be lower than that planned for the SSC, however, less scientific output would result.

The CERN strategy is to build an accelerator with the power of the LHC and discover the phenomena that are postulated to exist in the range of up to 1 trillion electron volts, including the Higgs Boson and other particles. After this level has been explored, larger instruments such as the SSC, or alternative technologies such as electron-positron linear colliders (see below), could be investigated. Joining CERN in building the LHC would be a way of postponing the decision on the SSC and waiting until either the budget atmosphere becomes more accommodating or until there is technological improvement. It would have the advantage over simple postponement of the SSC decision that it would keep U.S. high-energy physicists productively employed, since the LHC is intended to take the same amount of time to build as the SSC.

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[3] This discussion is largely based on the testimonies of Herwig Schopper and Carlo Rubbia, both of the European Organization for Nuclear Research (CERN). See *Superconducting Super Collider*, Hearings before the House Committee on Science, Space, and Technology, 100:1 (April 7-9, 1987), pp. 288-293, and *Status and Plans of the United States and CERN High Energy Physics Programs and the Superconducting Super Collider*, Hearings before the Subcommittee on Energy Development and Applications of the House Committee on Science and Technology, 99:1 (October 29, 1985), pp. 30-51.

[4] For technical details, see the European Organization for Nuclear Research, *Report of the Long Range Planning Committee to the CERN Council* (Geneva: CERN, 1987).

There are disagreements over this strategy: some scientists connected with CERN have urged the rapid construction of the SSC. The CERN Committee of Council, however, has refrained from endorsing or planning accelerators of SSC energies, choosing to concentrate on the intermediate step. The CERN council and the member nations have not yet formally committed themselves to the LHC. The proposal is at a much earlier stage than that for the SSC, suggesting that the United States could have a substantial influence on the plans for the LHC, should the Congress choose to participate in that project.

Risks and Benefits to Science

The principal scientific benefit of the LHC will be to permit U.S. high-energy physics to explore high energy levels at a lower total cost than with the SSC. If built, the LHC would be a world-class instrument. Whether or not the U.S. government participates, U.S. high-energy physicists will have access to the facilities. Given the international nature of the high-energy physics community, high-energy physics in the United States would not suffer greatly from international participation. Federal government participation in the LHC would serve to acknowledge this international aspect of the science budgeting process.

Although the phenomena of current scientific interest should be visible to both the LHC and the SSC, the lower energy levels of the LHC may preclude observation of some other interesting phenomena. In addition, building only the LHC means that physicists will be competing for limited experiment time. The LHC might also have fewer detectors than the SSC and will be competing with the Large Electron Positron collider, which could still be running, for experiment time. As a consequence, fewer experiments may be performed, and the cost per experiment could rise.

If just the LHC were built, there would be only one instrument worldwide capable of investigating phenomena in these high energy ranges. If it were shut down, either because of an accident or other mishap, work in whole areas of high-energy physics would stop, because there would be no other instrument to match its energy.

Moreover, joining the LHC project instead of building the SSC would mean that in the late 1990s, all the newest high-energy physics facilities would be in Europe: HERA in West Germany, and the Large Electron Positron collider and the LHC in Switzerland. To the extent that the training and other benefits land near the instrument site, the United States would cease enjoying these. On the other hand, these benefits affect mainly engineers and technicians; the professors and graduate students would be internationally mobile, as they are now.

Risks and Benefits to Technology

The technological risks and benefits for U.S. industry from the LHC would largely depend on the exact nature of U.S. participation and on the CERN procurement contracts. U.S. superconducting magnet makers and DOE often complain that the U.S. industry is excluded from CERN projects. Negotiating the LHC procurement is not likely to be simple because of the perceived technology spinoffs. The analysis that follows assumes that, if the United States contributes substantial funds to CERN, provisions will be made to ensure that U.S. superconducting magnet and equipment makers, as well as European manufacturers, supply the project with its technical requirements. Should U.S. industry be excluded, the commercial benefit of technology spinoffs to U.S. companies would be substantially reduced.

The pooling of U.S. and CERN technology will increase the likelihood that the superconducting magnets and other technical components will receive the attention of the best talent worldwide. As noted above, only in Europe has the manufacture of superconducting magnets for accelerators been undertaken in an industrial setting. Thus, the U.S. superconducting magnet industry stands to gain from an infusion of European technology. Furthermore, many of the same superconducting technology spinoffs that would result from building the SSC should also result from the LHC.

The spinoffs from the LHC are bound to be more widely distributed than those that might occur with the SSC. The superconducting magnets may be built by several companies of various nationalities. This contracting procedure would ensure the spread of superconducting technology to many countries, and the United States would not enjoy monopoly benefits that might be hoped to result from the SSC. The possibility of monopoly benefits may be illusory, however, since CERN may build the LHC even without the United States, ensuring a major European superconducting magnet effort at the same time as the U.S. effort related to the SSC. Japanese firms are also entering this industry.

Lastly, one obvious disadvantage of building the LHC is that it would be located outside U.S. borders. While U.S. construction firms and other suppliers might provide some inputs, the benefits of long-term regional economic development would flow to Europe. This case would not be unique: U.S. military installations located abroad also provide regional economic benefits. The LHC would be different, however, in that most military bases have few if any spinoffs.

Budgetary Risks and Benefits

Since the proposal for the LHC is much less developed than that for the SSC, the estimates of its costs are preliminary. Furthermore, the portion of the costs that would fall to the United States have not yet been negotiated.

Because it will be built in the Large Electron Positron collider tunnel and use the existing infrastructure and older CERN accelerators, the additional costs of the LHC will be primarily for superconducting magnets, cryogenics, and detectors. In his testimony last year, Herwig Schopper stated that the CERN Long Range Planning Committee had calculated that the costs would be between one-quarter and one-third of the costs of the SSC.[5] This would translate into roughly $1.1 billion to $1.5 billion.

However, it is unclear from Schopper's testimony or the Long Range Planning Committee's report what this figure includes. Nowhere in the report is there any discussion of the detector costs. As noted in Chapter III, the detectors for the SSC are projected to cost between $900 million and $1.2 billion, although DOE believes they can be built for $720 million. Because the LHC will have only two detectors and the SSC will have four, detector costs are likely to be substantially lower for the LHC than for the SSC. In addition, CERN estimates often exclude support provided to projects by laboratories of CERN and its members. Assuming, as an upper bound, that the LHC detectors cost as much as the two most expensive SSC detectors (a total of $700 million to $800 million) and that laboratory support work is roughly 50 percent of direct costs ($550 million to $750 million), the estimate for the complete LHC may be closer to between $2.4 billion and $3.1 billion.

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[5] Testimony of Herwig Schopper, *Superconducting Super Collider*, Hearings before the House Committee on Science, Space, and Technology, 100:1 (April 7-9, 1987), p. 291.

Should the United States join CERN in building the LHC, the U.S. contribution would have to be negotiated. CERN is supported by most Western European nations, many of whom have substantial resources for high-energy physics. They have shown their willingness to make large investments in accelerators: the Large Electron Positron collider is costing roughly $1.1 billion. On the other hand, the role of U.S. scientists and U.S. component manufacturers would also be open to negotiation. Presumably, the greater the U.S. contribution, the greater the U.S. role, and the negotiations promise to be complex.

This analysis assumes that the U.S. contribution to the LHC will fall between 25 percent and 33 percent of the total costs. The cost to the United States would then be between $600 million and $1.0 billion. Thus, joining CERN in the construction of the LHC instead of building the SSC without international contributions would result in a U.S. budget savings of between $3.5 billion and $4.5 billion, relative to the estimated cost of $4.5 billion to $5.1 billion for the SSC.

Design Risks

The design of the LHC is likely to be riskier than that of the SSC. The configuration of the LHC magnets, as currently conceived, would be much more complicated than that of the SSC. In order to produce high energy levels in the small circumference of 27 kilometers, very powerful magnets of 10 tesla would have to be built.[6] The SSC magnets are of 6.6 tesla and are considered very powerful by normal standards. The research program for the LHC magnets has modified the design of the magnets being built for the HERA accelerator in West Germany and achieved about 9 tesla in a small test magnet, but is still far from proving the technical and economic feasibility of those magnets.[7]

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[6] A tesla is a unit of magnetic strength, defined as one weber per meter squared (see glossary).

The superconducting magnets for the LHC may also require an unusual dual-bore design. The Large Electron Positron collider tunnel may not accommodate two additional rings of superconducting magnets. Consequently, each magnet may be required to contain bores for two separate proton beams, which will add technical complications. By contrast, the SSC's superconducting magnets, like the Energy Saver and Tevatron I magnets, have only one bore.

In order to achieve its high mass reach in a small space, the LHC has to increase the number of interactions among particles in its beams to achieve the desired event rate (luminosity). This might result in so many interactions, however, that the detectors are unable to track them properly. Conversely, if the LHC lowers its luminosity, it lowers its mass reach and may miss some phenomena of interest. Thus, while reusing the Large Electron Positron collider tunnel for the LHC would reduce the cost of the conventional facilities, it would increase the cost and functional risks of the technical components.

Because of the complex nature of the LHC's superconducting magnets and the fact that the LHC will be competing with the Large Electron Positron collider for time in the tunnel, the LHC may fall behind schedule. Moreover, although it is currently given the same schedule expected for the SSC, the time pressure may be removed if the United States cancels the SSC and joins CERN's project.

Political Risks

While the Congress was able to stop building the Isabelle particle accelerator at the Brookhaven National Laboratory for technical reasons and might be able to slow down other scientific programs, committing part of the U.S. science budget internationally will place

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7. Designers of the LHC hope to use superconducting magnet technology developed by the SSC research program.

more international constraints on Congressional actions. Additionally, CERN may decide not to build the LHC. If both the SSC and the LHC were deferred indefinitely or canceled, high-energy physics might stagnate or leadership might pass to Japan and the Soviet Union, both of which have high-energy physics programs. On the other hand, the LHC might become very attractive to CERN members if the United States shares the costs and lends prestige to the project by supporting it.

BUILD AN ELECTRON-POSITRON LINEAR COLLIDER

The choice of a proton-proton ring collider for meeting the objectives of high-energy physics is based on extending a known accelerator technology, albeit in a large increment. Physicists, however, can also use electron-positron linear colliders for many of the same experiments and some have suggested that, instead of building the SSC, the United States should build an electron-positron linear collider as its next major accelerator. Instead of building the SSC, the Congress could increase R&D funding for these accelerators and begin planning construction of an electron-positron linear collider.[8]

High-energy physics has traditionally had both proton and electron-positron accelerators, as they tend to complement each other scientifically. As costs rise, however, the high-energy physics community and the Congress will have to consider whether the U.S. science budget can continue to fund both types of accelerator.

Electron-positron linear colliders may require 15 to 20 years of research before they can achieve the energy levels of the SSC. The new accelerator technologies, however, are expected to be able to reach levels of energy approaching those of the LHC in the late 1990s.

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[8] For a technical version of this debate, see Freeman Dyson, "Alternatives to the Superconducting Super Collider," *Physics Today* (February 1988), p. 77. Responses from critics and his rejoinder appear in the May 1988 issue of *Physics Today*. For a detailed discussion of types of particle accelerators, see National Research Council, *Physics Through the 1990s: Elementary-Particle Physics* (Washington, D.C.: National Academy Press, 1986), pp. 98-131. CERN is also considering an electron-positron linear collider, called CLIC. See *Report of the Long Range Planning Committee to the CERN Council*, pp. 30-40 and Appendix II.

In fact, building such a machine is part of the agenda needed to advance accelerator technology in general.[9]

Electron-Positron Linear Colliders

An electron-positron linear collider accelerates electrons and positrons in a straight line into a collision with each other. Unlike the LHC or the SSC, these colliders have no rings: they simply use two particle sources and the power sources to accelerate the particles at opposite ends of a straight tunnel, analogous to holding two shotguns muzzle to muzzle and pulling the triggers at the same time. The simplicity saves the costs of superconducting magnets that are needed to keep high-energy particles moving in a circle.

These electron-positron colliders are attractive in that the particles need not have as much energy as the protons in the SSC to yield similar results. Because protons are composed of quarks and other particles, when two protons collide the effective energy available for scientifically interesting interactions is less than the total energy of the particles. The SSC beams of 20 trillion electron volts each will give only enough energy to create interesting interactions in the range of 3 trillion to 4 trillion electron volts. The rest of the energy will be used by interactions not of immediate interest. In an electron-positron collision, all of the energy is available for such interactions. A collision of electrons with positrons at 3 trillion to 4 trillion electron volts is thus equivalent to the collision of protons with protons at 40 trillion electron volts in the SSC. At present, there is no linear collider in operation that can reach such energies.

The reason electron-positron linear colliders may be important is that, unless there are unforeseen developments in accelerator technology, the SSC will probably be the last U.S. proton-proton accelerator: building a circular accelerator larger than 53 miles in circumference is difficult to conceive and likely to be very expensive. If accelerator energies are to increase, new types of accelerators must be developed. DOE already has a program to develop these. One Congressional option is to support the developing technology rather than the established one.

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[9] Department of Energy, *Report of the HEPAP Subpanel on Advanced Accelerator R&D and the SSC* (December 1985), p. i. This report is referred to hereafter as *The HEPAP Report on Accelerator R&D.*

The largest, and in fact the only, electron-positron linear collider built so far is the Stanford Linear Collider in Stanford, California. The collider is 2 miles long and has a collision energy of 100 billion electron volts. However, it is having problems producing the particles it is intended to study and has been temporarily shut down.

Using current technology from the Stanford Linear Collider, physicists cannot duplicate SSC experiments. Using this technology to produce energies comparable to those of the SSC, the collider would have to be 200 miles long, which would be prohibitively expensive. Based on the cost of the Stanford Linear Collider, a 200-mile-long facility necessary to match the SSC would cost $16 billion.[10]

Successful operation of the Stanford Linear Collider is an important step in confirming several design concepts of such colliders. Nevertheless, while the Stanford Linear Collider will provide useful information, its characteristics are quite different from those of a linear collider that can achieve several trillion electron volts, and thus it is not possible to simply scale up the Stanford Linear Collider.[11] Research is, therefore, focusing on improving the capabilities of electron-positron linear colliders.

The DOE panel on alternative accelerator design estimates that it will be five years before a clear direction in electron-positron linear colliders emerges. It may take an additional 10 to 15 years before a linear collider can be built that will have the same mass reach capabilities as the SSC.[12]

It might be much easier, however, to build an electron-positron linear collider that will approach the capabilities of the LHC. Despite its problems, the Stanford Linear Collider has begun to prove many of

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10. *The HEPAP Report on Accelerator R&D*, p. 35.

11. The Stanford Linear Collider's design is different from the likely design of future electron-positron linear colliders because it was constrained by pre-existing facilities.

12. *The HEPAP Report on Accelerator R&D*. Similarly, CERN does not expect technology for the CLIC, its own version of the electron-positron linear collider, to develop in less than 10 to 15 years.

the concepts needed for higher-energy electron-positron linear colliders: most of the problems seem associated with older technology incorporated into the Stanford Linear Collider from a previous accelerator.[13] Some of the recent research conducted at Stanford suggests that the time needed to complete a machine with a mass reach of 0.6 trillion to 1 trillion electron volts might be less than previously thought. Lastly, *The HEPAP Report on Accelerator R&D* suggested that design and construction of machines with mass reach levels between those of the Stanford Linear Collider and the SSC might become feasible by the early 1990s. Thus, an electron-positron linear collider at an intermediate energy level could be built in the late 1990s, assuming the current R&D program is successful. By comparison, even if the Congress approves construction of the SSC in early 1989, it will be at least eight years before the SSC is ready for experimental work.

Risks and Benefits to Science

The principal scientific benefit of building an intermediate range electron-positron linear collider to investigate phenomena at up to 1 trillion electron volts is that it would advance high-energy physics at a lower cost, freeing up funds for other science, including other high-energy physics. The range of up to 1 trillion electron volts would expand high-energy physics' current capabilities and permit investigation of many of the phenomena in the standard model at this energy level, including some versions of the Higgs Boson.

Compared with joining CERN in building the LHC, this machine would give U.S. high-energy physicists access to a state-of-the-art research instrument. It would also provide one more instrument worldwide on which to perform high-energy physics experiments. Moreover, it would lead U.S. physics through the design of the next generation of accelerators.

On the other hand, an electron-positron collider would have only one detector. While this reduces costs, it also means that fewer experiments can be performed, which reduces the scientific potential of the instrument. Electron-positron colliders, however, can run at higher interaction rates than can proton-proton colliders without overwhelming the detectors, producing the same number of interesting phenomena in less time.

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[13] See "More Setbacks at SLAC," *Scientific American* (October 1988), p. 25. See also, Mark Crawford, "Racing After the Z Particle," *Science* (August 26, 1988), pp. 1031-1032.

An intermediate-energy electron-positron linear collider carries more risk than the LHC of not being able to explore the highest reaches of the 1 trillion electron volts range as thoroughly as the SSC.

Risks and Benefits to Technology

Assuming CERN builds the LHC and the United States builds an electron-positron linear collider with a mass reach of 1 trillion electron volts, the European superconducting magnet industry would probably grow in sophistication relative to the U.S. industry. As noted, the LHC's superconducting magnets will have to be very powerful and sophisticated. By contrast, because they are linear and do not have to bend particle beams, electron-positron linear colliders use fewer, if any, superconducting magnets. Consequently, this part of the U.S. industry may fall behind, although the magnetic resonance imaging industry is still growing and has yet to take full advantage of the superconducting magnet technology that has been developed so far for the SSC.

Budgetary Risks and Benefits

Because much of the technology is as yet undeveloped, the preliminary cost estimates are especially unreliable. To a certain extent this estimate freezes the technology artificially, since physicists have just begun to examine ways to reduce these costs. Should these experiments present positive results, the preliminary estimates cited here would be obsolete.

The estimate contains three cost components: the linear structure, the power source, and other components such as detectors. Assuming acceleration gradients of 186 million electron volts per meter, an accelerator with a mass reach of 1 trillion electron volts would have to be 7 kilometers long, including an extra 30 percent in length for infrastructure. Using the $50 million to $100 million per kilometer suggested by *The HEPAP Report on Accelerator R&D*, the structural costs would total between $350 million and $800 million. Since the report was issued, power source costs have decreased dramatically. The report suggested that stored energy costs equivalent to those of the SSC would total $40 billion. Current experiments and anticipated manufacturing improvements suggest that $400 million to $800 million spent on a power source might be sufficient for an intermediate energy collider. Detectors, R&D, and other costs might add $250 million to $500 million. Thus, with the understanding that such an estimate is surrounded by a high degree of uncertainty, CBO's calculations suggest that such a machine would cost about $1 billion to $2 billion.[14]

Design Risks

Electron-positron linear colliders are still quite small in energy terms. They carry a high risk of never being able to deliver what they promise. It is quite possible that building larger scale electron-positron linear colliders could uncover unsuspected problems. Similarly, scientists may encounter obstacles in scaling up linear colliders that could make them more expensive than the SSC. Or they may be able to build an instrument with a mass reach of only 0.6 trillion electron volts rather than 1 trillion electron volts in the planned time, which would further lower the scientific potential. (The instrument would still be three times as powerful as the next most powerful electron-positron collider currently planned.) The uncertainty attached to the potential of these devices is high, although experts seem optimistic about the ability of the technology to succeed.

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[14] Many of the assumptions for these calculations are derived from *The HEPAP Report on Accelerator R&D*, pp. 33-39. For power source cost assumptions, see D.B. Hopkins and others, "An FEL [Free Electron Laser] Power Source for a TeV [trillion electron volt] Linear Collider" (paper presented at the LINAC 1988 Linear Accelerator Conference, Williamsburg, Virginia, October 3-7, 1988).

BUILD THE SSC USING HIGH-TEMPERATURE SUPERCONDUCTORS

There have been many recent advances in superconductivity at relatively high temperatures. The new discoveries are based on new materials, mainly ceramics, that exhibit superconducting properties (that is, lose all electrical resistance) at temperatures above that of liquid nitrogen. Low-temperature superconducting materials, such as those currently in the SSC, have to be cooled by using liquid helium. Liquid nitrogen is much cheaper and easier to work with than liquid helium. The massive use of superconductors by the SSC has raised the question of whether it would be better to defer construction of the SSC until new high-temperature superconducting cable is developed, which would lower the costs of cooling the superconducting magnets.

While the recent development of high-temperature superconductors has opened many new possible applications for superconductors, these applications promise to become a reality only after many years, perhaps decades in the case of high-energy applications, of further R&D. None of the high-temperature superconductors is ready for industrial applications and especially not at the high power levels necessary for the magnets that hold the SSC's proton beams on course in the accelerator rings. The high-temperature superconductors present exciting potential, but it is also possible that they will remain laboratory curiosities and never find useful applications. Even if they find useful applications, they may not be useful at energy levels sufficient to power the SSC magnets. By contrast, low-temperature superconductor technology is currently available to power the SSC.

Budgetary Risks and Benefits

The SSC Central Design Group has conducted a study to ascertain the impact of the new technology on the design and the cost of the SSC.[15] The study limits itself to the assumption that high-temperature superconducting magnets replace the planned low-temperature superconducting magnets while the size of the machine remains the same. It

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15. M. S. McAshan and Peter VanderArend, "A Liquid Nitrogen Temperature SSC" (report prepared for the SSC Central Design Group, April 1987).

examines the impact of the replacement on the design and the cost of the magnets, cryogenics, quench protection system, liquid nitrogen production, and operations.

The Central Design Group concluded that there would be a 3 percent reduction in total estimated costs if high-temperature superconductors were used in the SSC. The savings are clearly not enough to spur interest in delaying the project for at least 10 to 20 years for the development of high-temperature superconductors.

There might be savings in certain components of the SSC, but net savings are not likely to be large because other components may become more expensive. The cryogenic components are projected to cost $129 million.[16] Cost reductions in cryogenics by using liquid nitrogen instead of liquid helium would be in part offset by increased costs in the vacuum system. The low temperature of the liquid helium makes air liquefy and allows the easy maintenance of a vacuum. At a higher temperature the vacuum is more difficult to maintain and special pumps and a larger beam pipe assembly for the particle beams may be necessary. Even if material costs decline, other components of the magnets' cost--engineering, labor, and other components--are likely to rise because the new superconducting materials are difficult to handle.[17] It is therefore unlikely that the new high-temperature superconductors will be in a position to reduce substantially the costs of the SSC in the near future.

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[16] The complete ring system costs $1.3 billion, but many of these components, such as instrumentation, controls, and safety systems, would be required with any magnets. See SSC Central Design Group, *Conceptual Design of the Superconducting Super Collider* (Berkeley, Calif.: SSC CDG, 1986), p. 697. Costs were deflated using the DOE inflation index for energy research and nuclear construction.

[17] Robert Pool, "Superconductors' Material Problems," *Science* (April 1988), pp. 25-27.

APPENDIXES

APPENDIX A

TECHNOLOGY SPINOFFS FROM GOVERNMENT PROGRAMS

There is substantial literature concerning federal government technology programs and commercial innovation, much of it far beyond the purview of this report.[1] One can draw several themes relevant to the Superconducting Super Collider (SSC) from this literature. First, federal agencies have had the greatest success with spinoffs when they directly used the technology in question. (An important exception is in the area of health and agriculture.) The Department of Defense (DOD) and the National Aeronautics and Space Admininistration (NASA) felt they needed integrated circuits to fulfill their respective missions. While they may have envisaged eventual civilian applications (the contractors certainly did), they needed integrated circuits for the Minuteman II missile program and for the Apollo lunar mission. Similarly, military needs such as those for nuclear weapons, air defense, and intelligence programs created a government demand for computers. By contrast, much of the research performed by the Department of Energy (DOE) and the Synthetic Fuels Corporation, where the program's objectives were to champion technologies for private sector users, had little success.

Second, federal agencies played a substantial role in commercial development when they represented a large fraction of total demand. DOD and NASA, for instance, bought the first few million integrated circuits, representing all or nearly all demand at the outset of this technology. With computer technology, federal agencies were the first purchasers of virtually all new advances in technology during the 1940s, 1950s, and early 1960s.

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1. For a compendium of industry studies, see Richard R. Nelson, ed., *Government and Technical Progress, A Cross-Industry Analysis* (New York: Pergamon Press, 1982). For a more recent study, see Kenneth Flamm, *Creating the Computer: Government, Industry and High Technology* (Washington, D.C.: The Brookings Institution, 1988). In the case of integrated circuits, see Philip Webre, "Technological Progress and Productivity Growth in the U.S. Semiconductor Industry" (Ph.D. Dissertation, American University, 1983), pp. 93-111.

Third, even where federal agencies played a crucial role in the development of a particular technology, no single program or instrument was responsible for the entire development of complex devices like computers or integrated circuits. The history of computer technology since the 1940s shows each federal research project adding one new element to the modern computer.[2] Occasionally, the stated mission of the computer would change according to the technology that was developed.

Lastly, many promising technology spinoffs proved to be dead ends. Again, the history of integrated circuits is instructive. For at least 10 years, the federal government supported the development of products designed to perform the function of integrated circuits, but the vast majority of the funds probably went into projects which ended in failure. On the other hand, even programs that initially prove unproductive may make important contributions to other projects. For instance, during the late 1950s, the U.S. Navy funded thin film technology as an alternative to integrated circuits. While the project as a whole came to nothing, advances in photolithography were made that later proved important in the development of integrated circuits.[3]

The importance of these lessons is that the SSC should not be expected to result in more than one or two major technological developments, if any. Moreover, the technological fields in which the SSC is likely to play a role are limited. The SSC will represent the bulk of the market for superconducting magnets during its construction. Consequently, according to the above analysis, the SSC may prove important. (A fuller discussion of the SSC and superconducting magnets can be found in Chapter II of this report.) But outside this field, the SSC may not contribute as greatly to technological progress. Rather, the SSC looks like any other sophisticated consumer of computers and other such instruments, and hence it is no more or less likely to produce an important advance than any other major laboratory.

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[2] Flamm, *Creating the Computer*, Chapters 3 and 4.

[3] Webre, "U.S. Semiconductor Industry," pp. 103-107.

SPINOFFS FROM THE PARTICLE PHYSICS PROGRAM

Research programs in high-energy physics differ from other scientific research studies in one important property: usually these research projects require large investments in the development of new technological tools for research. It is intrinsic to the type of research conducted by high-energy physicists that better and bigger tools are needed to further knowledge. Thus, the chance of a technology spinoff from a particle physics program is enhanced simply because it invests in the development of advanced technology for its own use.

Another unique contribution of particle physics is its scientific role in providing the intellectual basis for the conception of new technologies. Many advances in electronics, and in medical technologies, have their roots in particle physics research. From the magnetron in microwave ovens to fusion reactors, there is a vast range of technologies whose conception can be attributed to particle physics.

Most technological spinoffs from research in high-energy physics have repeat applications for new research in the same field. The technology developed for one accelerator becomes the basis of the next generation of the accelerator. This is most evident in the technology being used for the SSC, much of which was developed at the Fermi National Accelerator Laboratory (Fermilab) for the Tevatron I.

As discussed above, one important trait of all spinoffs from investments in research is that a technology can rarely be attributed wholly to a single research project. Success is usually a cumulative effect of many research programs, procurements, and advances in the basic science. None of the examples of spinoffs described below can be attributed to a single project. In fact, most successful spinoffs that move out of the laboratory evolve only after a concerted effort to develop the technology further for its own sake.

Electronics

The semiconductor industry has gained heavily from research in particle physics. A substantial portion of the knowledge used in the invention of the transistor came from early research on atomic nuclei.

The manufacturing process for integrated circuits today relies heavily on processes rooted in particle physics experimentation.

One such process is ion implantation, a technique in which ions or charged particles are implanted on the surface of a material thereby altering its physical, chemical, electrical, or optical properties. Ion implantation can provide the desired characteristics to metals, alloys, ceramics, and even insulating materials and polymers.[4]

The technique of ion implantation has origins in particle physics research. Scientists developed the technology to bombard an atomic nucleus with ions, and the equipment used in ion implantation is very similar. This process, which was developed in the early 1960s to study a natural phenomenon, has now spurred research of its own to find more applications in industry.

Ion implantation has become the preferred procedure in the manufacture of integrated circuits. It is also aiding in the development of new semiconductors for faster, cheaper, and smaller circuits by implanting a very thin layer of silicon on an insulating material.

Ion implantation is also used to change the chemical and mechanical properties of metals. It can make them harder, increase their resistance to corrosion, lower their friction, and change their magnetic properties. For example, implanting nitrogen in metal surfaces has reduced wear 1,000 times. Such advances are being exploited in the manufacture of engine components, ball bearings, and precise tools and dyes. Another important application that could become highly beneficial is the use of nitrogen-implanted titanium alloy for hip prostheses. Nitrogen implantation will increase the longevity of these devices by reducing wear from friction and chemical degradation.

Medicine

In the medical field, there have been vast improvements in diagnosis and treatment techniques as a result of particle physics spinoffs. Radio-isotopes or radioactive atomic particles, first produced in particle physics research, have since found applications in medical diagnosis. Nuclear medicine and radiology have grown in their capabilities in recent years as a result of the availability of better technology. More and more procedures using radio-isotopes for inpatient and outpatient care are used every year: one out of eight people will at some point receive radiation therapy for cancer.[5] In nuclear medicine, an industry has been created to provide accelerators, detectors, imaging systems, and related services.

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[4] For a more detailed description of the use of ion implantation in industry, see S. Thomas Picraux and Paul S. Peercy, "Ion Implantation of Surfaces," *Scientific American*, vol. 252 (March 1985).

Radio-isotopes were first artificially produced by particle physicists before the age of accelerators; now accelerators have made the process easier. Most radio-isotopes used in medicine today are created commercially using accelerators, and almost all pharmaceutical companies operate accelerators for manufacturing and research: short-lived radio-isotopes are now produced in vast quantities by these pharmaceutical companies. In 1982, $130 million worth of pharmaceuticals based on isotopes were sold.[6] Diagnoses using isotopes are a major advance over other diagnostic techniques like exploratory surgery and heart catheterization.

Advances in radiography and software used to recognize patterns have been applied to computer-aided tomography, or CAT scanning. Another important diagnostic technique derived from particle physics is magnetic resonance imaging. Recent advances in studying living organisms have come from tagging monoclonal antibodies with radio-isotopes. Another contribution of particle physics to medicine is the direct use of accelerators in treatment and therapy: particle accelerators are now used to treat cancer patients, and X rays from radio frequency accelerators are used in radiotherapy.

Superconducting Magnets

One of the largest direct effects of particle physics has been on the development of the superconductor industry, which emerged primarily from the research at Fermilab to develop the magnets for the Tevatron I collider.

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[5] Waldemar Scharf, *Particle Accelerators and Their Uses, Part 2* (New York, N.Y.: Harwood Academic Publishers, 1986), p. 786.

[6] Paul A. David, David Mowery, and W. Edward Steinmueller, "The Economic Analysis of Payoffs from Basic Research--An Examination of the Case of Particle Physics Research" (paper prepared for the Center for Economic Policy Research, January 1988), p. 55.

When Fermilab designed the Energy Saver, the key element was low-temperature superconducting magnets; using these magnets increased the power of the accelerator and reduced its consumption of electric power. Such magnets had been used in other accelerators, but there was no commercial source that could provide the 990 magnets needed for the Tevatron. Fermilab set up its own facilities and, together with commercial contractors, developed the complete procedure from making the superconducting cable to the particle beam correction system and quench protection systems for these magnets.[7]

Once it was shown how niobium-titanium cables could be wound to make low-temperature superconducting magnets, the manufacturers developed other uses for the product. It is possible that superconductors would have eventually found commercial applications in any case, but the impetus provided by Fermilab accelerated the process and bore the initial cost of research and development. The biggest use of superconducting magnets today is in magnetic resonance imaging machines. While the Tevatron I cannot be awarded all the credit for the establishment of this industry, in this particular case it had the largest impact of any previous high-energy research project on the development of a technology spinoff.

Other Spinoffs

Other spinoffs in the history of accelerators have come from research on the subsystems of the accelerators. Applications have been found for components developed for detectors, vacuum systems, magnets, particle storage and acceleration, and communication and computer systems in industry. For example, photomultiplier tubes developed for particle physics detectors are now widely used in medical instruments, and advances in vacuum technology came from initial research in accelerators. While most advances in accelerator subsystems are limited to building better accelerators, there are some that have influenced the development of other technology. For example, the need to collect and process vast quantities of accelerator data quickly had some impact on advances in computer networks and processors.

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[7] Barbara Gross Levi and Bertram Schwarzschild, "Super Collider Magnet Program Pushes Toward Prototype," *Physics Today*, vol. 41, no. 4 (April 1988), pp. 17-21.

APPENDIX B

TECHNOLOGY SPINOFFS FROM CERN ACCELERATOR RESEARCH

In 1984, the European Organization for Nuclear Research (CERN) published a report on the economic and commercial spinoffs of its high-energy physics program in Geneva, Switzerland.[1] This study (referred to as the *CERN Contracts Study*) concentrated on the secondary economic effects of the procurement contracts let by CERN. The study's intention was to determine whether firms that sold high-technology goods to CERN experienced subsequent increases in non-CERN sales. The conclusion was that CERN contracts generated 3 Swiss francs in non-CERN sales for each Swiss franc in CERN sales (all francs cited here are Swiss francs). This appendix examines the study for substance, method, and applicability to U.S. circumstances. It shows that the study substantially overstates the added value of CERN contracts to the economy, although not to the firms involved. Moreover, largely because of differences in technology, many of the report's conclusions may not be applicable to the United States.

Summary of the CERN Contracts Study

The *CERN Contracts Study* divided the economic effects of CERN into three categories: primary economic effects, secondary economic effects, and macroeconomic multiplier effects. The first category is the economic usefulness of the research results themselves. In the case of CERN, or the Superconducting Super Collider (SSC) in the United States, the research results are not expected to pay for themselves economically for decades, if ever. While early economic use of these results would be welcome, these projects are being undertaken for the sake of knowledge and any other use of the results is considered fortuitous. The third category, multiplier effects, is simply the stimulus to the economy that results from all government purchases of goods and services. The stimulus would be roughly the same whether the government were building a highway or a particle accelerator. The *CERN Contracts Study* focuses on neither of these, but rather concentrates on the benefits to the firms that provide high-technology equipment under contract to CERN.[2]

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[1] M. Bianchi-Streit and others, "Economic Utility Resulting from CERN Contracts (Second Study)" (prepared for the European Organization for Nuclear Research, Geneva, Switzerland, December 11, 1984). Reprinted in *Superconducting Super Collider*, Hearings before the House Committee on Science, Space, and Technology, 100:1 (1987), p. 151. This study is referred to hereafter as the *CERN Contracts Study*. Note also that this study is independent of a previous study, which covered similar topics for an earlier period. The Congressional Budget Office did not analyze the first study.

The study's method is straightforward: 160 sample high-technology firms that received CERN contracts during the 1973-1982 period were asked how much in additional sales the CERN contracts had generated or would generate during the 1973-1987 period. (Since interviews for the study were conducted between May of 1982 and June of 1984, a substantial portion of the stated gain in sales was, in fact, a forecast.) While the questions asked covered a range of topics--such as how CERN contracts affected management practices, quality control, research and development, and production techniques--the heart of the questioning related to additional sales. For instance, managers were asked to estimate how much CERN contracts had improved production techniques and then estimate how much the improved production techniques had increased, or would increase, sales by 1987. Furthermore, the answers were to be focused only on markets relevant to CERN. For example, unless specifically affected, consumer goods divisions of CERN contractors were excluded from the survey. While the survey intent was straightforward, the range of questions was complex enough to minimize deliberate exaggeration by the contractors.

Once tabulated, the results were screened for irregular data before being extrapolated to the universe of 519 high-technology CERN contractors.[3] The raw data results suggested that each franc in CERN sales produced 4.2 francs in added sales. Especially in the electronics,

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[2] The *CERN Contracts Study* did not examine what may be the largest spinoff of pure research projects: the training of the next generation of scientists. The authors of the *CERN Contracts Study* acknowledged that quantifying the secondary effects completely was impossible. See Chapter II of this report.

[3] Of CERN's 6,000 suppliers, the *CERN Contracts Study* classified 519 as "high technology," although the study did not define this term. The subsequent tabulations included steel and welding, which are not often classified as high technology.

TABLE B-1. SALES TO CERN AND NON-CERN MARKETS, BY INDUSTRIAL CATEGORY (In millions of 1977 Swiss francs)

	Electronics, Optics, Computers	Electrical Equipment	Vacuum, Cryogenics, Super-conductivity	Steel and Welding	Precision Mechanics	Total
Net Non-CERN Sales	2,245	1,025	400	255	155	4,080
CERN Sales	537	472	152	104	111	1,378
Ratio of Net Non-CERN Sales to CERN Sales	4.7	2.2	2.6	2.4	1.4	3.0[a]

SOURCE: M. Bianchi-Streit and others, "Economic Utility Resulting from CERN Contracts (Second Study)" (prepared for the European Organization for Nuclear Research, Geneva, Switzerland, December 11, 1984). Reprinted in *Superconducting Super Collider*, Hearings before the House Committee on Science, Space, and Technology, 100:1 (1987), p. 151.

NOTE: Details may not add to totals because of rounding.

CERN = European Organization for Nuclear Research.

a. Average of ratios.

optics, and computer industries, however, there were outliers: here the CERN franc produced 7.2 francs. The extrapolated results were tabulated by sector (see Table B-1). The net corrected benefit of each CERN franc to recipient firms was 3 francs.[4] This benefit applies to the high-technology suppliers exclusively, since they were the focus of the CERN study.

The authors of the *CERN Contracts Study* performed an additional test to determine the overall accuracy of the managers' sales forecasts. The study included 40 firms that had participated in an earlier study that used the same method. Comparing the forecasts made by these firms' managers with the subsequent actual events indicated that, while individual forecasts were often wrong, the aggregate forecast was close to actual overall sales. Tests suggested the differences between actual and forecasted sales were not statistically significant. The *CERN Contracts Study* therefore assumed that, on average, managers' forecasts would prove to be accurate.

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[4] Among the other factors adjusted for was the effect of the CERN contracts before 1973. The study assumed that non-CERN contracts won by CERN contractors during 1973-1975 resulted from previous CERN work and should not be counted in the 1973-1982 total. Such contracts turned out to be 15 percent of the total.

Assumptions

The central, and perhaps flawed, assumption of the *CERN Contracts Study* is that 100 percent of the sales of CERN contractors are new sales to the economy; that is, these sales do not come at the cost of fewer sales going to firms that do not have CERN contracts. The *CERN Contracts Study* provides some supporting arguments for this 100 percent "additionality" assumption. It is nevertheless an assumption and, to the extent it is incorrect, CERN is merely rearranging sales rather than creating new ones. While such a rearrangement of sales is of great benefit to the firms involved, from a public policy perspective the question naturally arises of why a public agency, whether CERN or the U.S. Department of Energy, should spend money in order to shift sales to one favored group of firms. The following paragraphs discuss the *CERN Contracts Study* assumption and how it is contradicted throughout the study itself.

While the assumption of 100 percent additionality has some merit, it is given no statistical or anecdotal support in the study. It is a polar assumption in the sense that it is at the extreme end of the range of possibilities. At the other end of the range is the assumption that CERN contracts generate no additional sales in the aggregate and that the CERN contractors are merely diverting sales that would have gone to other firms.[5] This second polar assumption is the more conventional one, and thus the burden of proof lies with the *CERN Contracts Study.*

The authors of the study give two arguments in support of their additionality assumption:[6]

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[5] An even more extreme position would argue that if the government crowded out private investment in the credit markets, research and development spending by CERN would reduce the funds available for private investment and so reduce contracts overall.

[6] *CERN Contracts Study*, p. 5.

- The relevant markets are growth markets, so no firm is actually taking sales from other firms.
- CERN buys only leading-edge products in these markets, and, by improving the quality of its suppliers, forces the competitors to improve also.

The first argument ignores the concept of baseline rates of growth. If a market is growing independently of CERN sales, then firms in those markets should expect to see sales growth. Investors in these firms would normally regard the failure to grow as indicative that something was wrong with the firm's management, product mix, or marketing. While no European firm may lose already existing sales to CERN contractors, CERN contracts may very well depress the sales growth of non-CERN contractor firms.

The second argument is simply overstated. Not every piece of equipment in CERN's laboratories leads the state of the art in its particular field. There will be certain components that are completely novel and other components that have substantial modifications and improvements. But to argue that CERN is simultaneously providing leadership in all aspects of the high technology it touches is to ignore the incremental and cumulative nature of scientific advance.[7] Like the first argument, this argument ignores improvements in technology that are occurring independently of CERN.

The assumption of 100 percent additionality is also regularly contradicted in the study. One of the major benefits the study claims for CERN contractors is that the contractors can use CERN as a reference. The study cites one case where a firm used its CERN contracts as the basis for admission to a trade association, "and, as a result, was able to obtain an increased number of [non-CERN] contracts."[8] The use of CERN as a reference for admission to a trade association, however, suggests a rearrangement rather than an expansion of sales. An expansion would come from the introduction of new products or from cost reduction.

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[7] In the United States, many government programs involving high technology are not at the leading edge of their particular field. For instance, the SSC design includes "off the shelf" components, such as microcomputers for the control of the rings of superconducting magnets and commercially developed networks to link these computers. See SSC Central Design Group, *Conceptual Design of the Superconducting Super Collider* (Berkeley, Calif.: SSC CDG, 1986), pp. 473-476.

[8] *CERN Contracts Study*, p. 11.

In another example cited by CERN, a small firm that supplied CERN with "standard, but specialized, hydraulic equipment" became the industry standard, increasing sales and exports. While there may be some increase in sales as a result of the benefits of standardization--consumers benefit by not having to compare and choose among competing equipment standards--these are offset by sales lost by the purveyors of alternative standards.[9] In this case, therefore, there will be some net gain in aggregate sales, but there will also be some losses for other providers of standard, but specialized, hydraulic equipment, showing that sales are once again being redistributed.

In sum, CERN probably has, by pushing technology forward, increased aggregate sales in high-technology products. However, there is no supporting evidence offered for, and a substantial amount of evidence against, the assumption that all or any substantial portion of the new sales obtained by CERN contractors were not diverted from firms without CERN contracts.

Applicability to U.S. Circumstances

In its justification of the additionality assumption, the *CERN Contracts Study* argued that it is "an efficient mechanism for keeping European industry abreast of international competition."[10] Simply put, the argument is that CERN contracts allow European suppliers to keep up with U.S. and Japanese suppliers of electronic goods and other high-technology products. In fact, the earlier CERN study found that roughly 33 percent of added sales came from substitution for imports coming from outside Europe, and that a further 30 percent represented exports to non-European countries.[11]

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[9] These losses could be magnified if the "wrong" standard--that is, one that limits future technology development--is chosen. See Paul David, "Some New Standards for the Economics of Standardization in the Information Age" (paper prepared for the Center for Economic Policy Research, Stanford University, October 1986).

[10] *CERN Contracts Study*, p. 5.

[11] From a strictly European perspective, excluded imports or new exports are 100 percent new sales.

The U.S. industry is in a very different position. While U.S. high-technology industries have lost part of their competitiveness to Japan's and other countries' high-technology industries, these losses have occurred to a large extent among products of lower technical sophistication, such as consumer products.

The microcomputer market is a case in point. (The emphasis is on the electronic and computer goods industries because over half of the added sales measured by the *CERN Contracts Study* occurred in electronics, optics, and computers. See Table B-1.) Imports to the United States from Korea, and other newly industrialized Asian countries, consist mainly of less sophisticated IBM-compatible personal computers. IBM, Compaq, Apple, SUN, and other U.S. companies still control the more technologically advanced segment of that market. Since scientists and technicians working on particle accelerator physics need the best equipment available, in the field of microcomputer technology they will be pushing for advances in the segment of the market the United States already dominates. Of course, not all markets divide as neatly as the microcomputer market: Japan, for instance, has made substantial inroads into markets for leading-edge semiconductors and semiconductor manufacturing equipment.

One of the benefits of CERN contracts mentioned in the study is that they help small firms to export to other European Community nations. The barriers to interstate commerce in the United States are nowhere near as high as they are in Europe. U.S. industries share legal traditions and systems, language, professional and trade journals and magazines, and trade associations. Given this lack of internal barriers, small firms in the United States should need little help to ship elsewhere in the United States.

APPENDIX C

COST INCREASES IN DOE ACCELERATORS

The tables in this appendix present detailed information on the increases in the construction costs of Department of Energy accelerators from their initial submission as a construction project to final completion. The data here are derived from DOE budget requests. All estimates are in current dollars. (For constant dollar comparisons, see Chapter III of this report.)

TABLE C-1. CHANGES IN THE COST OF THE ENERGY SAVER ACCELERATOR (In thousands of current dollars)

Category	Initial Estimated Cost	Final Estimated Cost
Engineering, Design, and Inspection	4,500	2,700
Construction Costs		
Magnets	13,500	38,300
Refrigeration	10,000	5,600
Power supplies and controls	850	1,600
Radio frequency source	1,300	200
Extraction	900	a
Special facilities	600	1,000
Conventional facilities	1,950	a
Total, construction	29,100	46,700
Contingency	5,300	1,400
Research and Development	28,900	68,668
Other Costs	6,000	13,000
Total	73,800	132,468

SOURCE: Congressional Budget Office, derived from Department of Energy budget requests for fiscal years 1979 and 1982.

a. Not separately included in DOE's 1982 budget request.

TABLE C-2. CHANGES IN THE COST OF THE TEVATRON ACCELERATOR (In thousands of current dollars)

Category	Initial Estimated Cost	Final Estimated Cost[a]
Hardware Costs		
Engineering, Design, and Inspection	4,200	10,100
Construction Costs		
Experimental areas	7,300	11,600
Ring and beam line housing	3,300	12,700
Antiproton source	10,400	23,500
Accelerator components	7,600	12,300
Subtotal	28,600	60,100
Contingency	6,700	13,800
Total, hardware costs	39,500	84,000
Other Development Costs		
Research and Development	18,800	50,504
Detectors	20,000	55,353
Total, other development costs	38,800	105,857
Offsets		
Total Project Costs	78,300	189,857
Foreign Contributions for Detectors	-7,800	-15,654
Net U.S. Costs	70,500	174,203

SOURCE: Congressional Budget Office, derived from Department of Energy budget requests for fiscal years 1981 and 1987. Details on foreign contributions for detectors from Fermilab budget activity reports, 1981-1985.

[a] Does not include $8.9 million in pre-1981 costs incurred during the conceptual design phase, which DOE no longer includes in its estimate of project costs.

GLOSSARY

These definitions are mostly taken or derived from National Research Council, *Physics Through the 1990s: Elementary Particle Physics* (Washington, D.C.: National Academy Press, 1986).

Absolute zero. The lowest possible temperature defined by the cessation of vibration of molecules. Zero degrees Kelvin.

Accelerator. A device that increases the energy of charged particles such as electrons and protons.

Antimatter. Matter composed of antiparticles, for example, antiprotons, antineutrons, antielectrons, instead of ordinary protons, neutrons, electrons.

Antiparticle. Each particle has a partner, called an antiparticle, which is identical except that all chargelike properties (electric charge, strangeness, charm, for example) are opposite to those of the particle. When a particle and its antiparticle meet, these properties cancel each other out in an explosive process called annihilation. The particle and antiparticle can then disappear and other particles be produced.

Antiproton. The antiparticle partner of the proton.

Atom. The smallest unit of a chemical element, approximately 1/100,000,000 centimeter in size, consisting of a nucleus surrounded by electrons.

Beam. A stream of particles produced by an accelerator.

CERN. The European Organization for Nuclear Research, located near Geneva, Switzerland, and supported by most of the nations of Western Europe.

Circular accelerator. An accelerator in which the particles move around a circle many times, being accelerated further in each revolution.

Collider. When a high-energy particle collides with a stationary target, a large portion of the energy resides in the continuing forward motion. Only a small portion of the energy is available for creating new particles. In a collider, collisions take place between high-energy particles that are moving toward each other. In such an arrangement, most of the energy is available for creating new particles.

Cosmology. The parts of astrophysics and astronomy having to do with the large-scale behavior of the universe and its origin.

Cryogenics. The science and technology of producing and using very low temperatures, even approaching absolute zero (zero degrees Kelvin).

DESY. Deutsches Electronen Synchrotron. The laboratory in Hamburg, Federal Republic of Germany.

Electromagnetic force or interaction. The long-range force and interaction associated with the electric and magnetic properties of particles. This force is intermediate in strength between the weak and strong forces. The carrier of the electromagnetic force is the photon.

Electron. An elementary particle with a single negative unit of electrical charge and a mass 1/1,840 that of the proton. Electrons surround an atom's positively charged nucleus and determine the atom's chemical properties. Electrons are members of the lepton family.

Electron volt. The amount of energy of motion acquired by an electron accelerated by an electric potential of one volt: MeV, million electron volts; GeV, billion electron volts; TeV, trillion electron volts.

Electroweak force or interaction. The force and interaction that represents the unification of the electromagnetic force and the weak force.

Elementary particle. A particle (piece of matter) that has no other kinds of particles inside it and no subparts that can be identified. Hence, the simplest kind of matter.

Elementary-particle physics. The area of basic science whose goal is to determine and understand the structure and forces of the most basic constituents of matter and energy. Synonymous with high-energy physics.

Fermilab. The Fermi National Accelerator Laboratory in Batavia, Illinois.

GeV. Giga electron volt, a unit of energy equal to one billion (10^9) electron volts.

Gluon. A massless particle that carries the strong force.

Hadron. A subnuclear, but not elementary, particle composed of quarks, including protons, antiprotons, and neutrons. These particles all have the capability of interacting with each other via the strong force.

HERA. An electron-proton circular collider, located at the DESY laboratory in Hamburg, Federal Republic of Germany.

Higgs Boson. See Higgs mechanism and particle.

Higgs mechanism and particle. A mechanism that may explain the origin and value of the mass of all or some of the elementary particles. The mechanism includes a proposed set of particles called Higgs particles or Higgs Bosons.

High-energy physics. Another name for elementary-particle physics. The name arises from the high energies required for experiments in this field.

Ions. Atoms or molecules that have a net electrical charge.

Kelvin. A scale of temperature. Zero degrees Kelvin (absolute zero) is equivalent to minus 273 Celsius or minus 523 degrees Fahrenheit.

LEP. Large Electron Positron collider. A circular electron-positron collider with a maximum design energy of about 200 GeV being constructed at CERN, Switzerland.

Lepton. A member of the family of weakly interacting particles, which includes the electron, muon, tau, and their associated neutrinos and antiparticles. Leptons are not acted on by the strong force but are acted on by the electroweak and gravitational forces.

Linear accelerator. In this type of accelerator, particles travel in a straight line and gain energy by passing once through a series of electric fields.

Luminosity. A measure of the rate at which particles in a collider interact. The larger the luminosity the greater the rate of interaction.

Magnet. A device that produces a magnetic field and thus causes charged particles to move in curved paths. Magnets are essential elements of all circular accelerators and colliders, as well as of many particle detectors.

Magnetron. A device used to generate microwaves.

Mass. The measure of the amount of matter in a particle and an intrinsic property of the particle.

Mass reach. The highest level of elementary-particle mass that an accelerator can produce with regularity. This number involves a combination of the beam energy levels and the luminosity. Proton colliders have a lower mass reach than electron-positron colliders of the same beam energy, because the protons they use are composed of quarks and gluons. Each of these has only a fraction of the proton's total energy.

MeV. Mega electron volt, a unit of energy equal to one million electron volts.

Molecule. A type of matter made up of two or more atoms.

Muon. A particle in the lepton family with a mass 207 times that of the electron and having other properties similar to those of the electron. Muons may have a positive or negative electrical charge.

Neutron. An electrically uncharged, strongly interacting particle with mass slightly greater than that of the proton; a constituent of all atomic nuclei except hydrogen.

Nucleon. A neutron or a proton.

Nucleus. The central core of an atom, made up of neutrons and protons held together by the strong force.

Particle. A small piece of matter. An elementary particle is a particle so small that it cannot be further divided; it is a fundamental constituent of matter.

Particle detector. A device that is used to detect particles that pass through it.

PEP. An electron-positron circular collider with a maximum energy of 36 GeV, located at the Stanford Linear Accelerator Center in Stanford, California.

PETRA. An electron-positron circular collider with a maximum energy of 46 GeV, located at the DESY laboratory in Hamburg, Federal Republic of Germany.

Photon. A unit of electromagnetic energy. A unique massless particle that carries the electromagnetic force.

Positron. The antiparticle of the electron.

Proton. A particle with a single positive unit of electric charge and a mass approximately 1,840 times that of the electron. It is the nucleus of the hydrogen atom and a constituent of all atomic nuclei.

Quantum mechanics. The mathematical framework for describing the behavior of photons, molecules, atoms, and subatomic particles. According to quantum mechanics, the forces between these particles act through the exchange of discrete units or bundles of energy called quanta.

Quarks. The family of elementary particles that make up the hadrons. The quarks are acted on by the strong, electroweak, and gravitational forces. Five are known: up, down, strange, charm, and bottom. A sixth, called top, is expected to exist.

Scattering. When two particles collide, they are said to scatter off each other during the collision.

SLC. Stanford Linear Collider, a linear electron-positron collider with an initial total energy of about 100 GeV at the Stanford Linear Accelerator Center in Stanford, California.

SSC. See Superconducting Super Collider.

Standard model. A collection of established experimental knowledge and theories in particle physics that summarizes the present understanding of that field. It includes the three generations of quarks and leptons, the electroweak theory of the weak and electromagnetic forces, and the quantum chromodynamic theory of the strong force. It does not include answers to some basic questions such as how to unify the electroweak forces with the strong or gravitational forces.

Storage ring. An accelerator-like machine composed of magnets arranged in a ring used to store circulating particles or to act as a collider. Sometimes a synonym for a collider.

Strong force or interaction. The short-range force and interaction between quarks that is carried by the gluon. The strong force also dominates the behavior of interacting mesons and baryons and accounts for the strong binding among the components of an atom's nucleus.

Superconducting magnet. See Superconductivity.

Superconducting Super Collider (SSC). A design being developed in the United States for a circular proton-proton collider with a total energy that could be as high as 40 TeV.

Superconductivity. A property of some metals that when they are cooled to a temperature close to absolute zero, their electrical resistance disappears. Magnets with superconducting coils can produce large magnetic fields while keeping size and power costs small.

Synchrotron. A type of circular particle accelerator in which the frequency of acceleration is synchronized with the particle as it makes successive orbits.

TeV. Tera electron volt, a unit of energy equal to one trillion (10^{12}) electron volts.

Tesla. A unit of magnetic strength, defined as one weber per meter squared.

Tevatron. A complex of accelerator facilities and beam lines at Fermilab. The main facility, called Tevatron I in this report, is a circular proton-antiproton collider with a total energy of 2 TeV. Tevatron II is an addition allowing the particle beams to be directed against a fixed target.

TRISTAN. A circular electron-positron collider with a total energy of 60 to 70 GeV under construction in Tsukuba, Japan.

Unification theories. Theories of forces in which the behavior of different kinds of forces is described by a unified or single set of equations and has a common origin. For example, the electric and magnetic forces are unified in the theory of electromagnetism.

Weak force or interaction. The force and interaction that is much weaker than the strong force, but stronger than gravity. It causes the decay of many particles and nuclei.

Weber. A unit of magnetic flux that, in linking a circuit of one turn, produces an electromotive force of one volt as it is reduced to zero in one second. One weber per meter squared is equal to one tesla.

X rays. Photons produced when atoms in states of high energy decay to states of lower energy.

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